

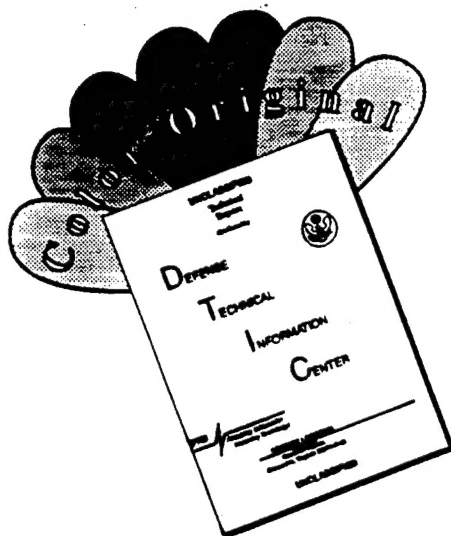
REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 9 OCT 95	3. REPORT TYPE AND DATES COVERED (Annual) 9 SEP 94-8 OCT 95		
4. TITLE AND SUBTITLE Human Factors in Tele-Inspection and Tele-Surgery:		5. FUNDING NUMBERS DAMD17-94-C-4125		
6. AUTHOR(S) Thomas B Sheridan, James Thompson, Jianjuen Hu, Mark Ottensmeyer, Jie Ren				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology  Cambridge, MA 02139		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  U.S. Army Medical Research and Materiel Command, Fort Detrick, MD 21702-5012		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution unlimited		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) In telesurgery a physician operates on a remote patient through a two-way communication and telerobot link. This first-year progress report describes development of a telesurgical simulator with force reflection and time delay, simulating what occurs with satellite communication. Also developed was a remotely controlled endoscopic tool. Using the simulator, preliminary experiments have been conducted with human subjects to evaluate alternative means to stabilize control movements under time delay, including a new technique combining "sliding" control with "fuzzy" control logic. Other experiments were conducted on "cooperative" manipulation where remote telemanipulation is combined with manipulation by a human assistant working local to the patient. Included with the latter are developments of computer graphical aids for communication between surgeon and assistant. Planned future experiments are described for both delay compensation and cooperative manipulation.				
14. SUBJECT TERMS telesurgery, telemedicine, remote control		15. NUMBER OF PAGES 51		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)  
Prescribed by ANSI Std Z39-18  
298-102

19951208 034

# DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF COLOR PAGES WHICH DO NOT REPRODUCE LEGIBLY ON BLACK AND WHITE MICROFICHE.

AD \_\_\_\_\_

CONTRACT NUMBER: DAMD17-94-C-4125

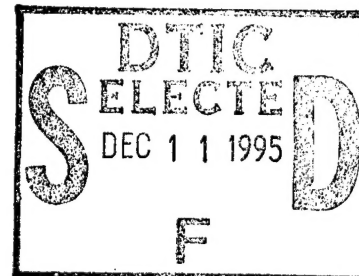
TITLE: Human Factors in Tele-Inspection and Tele-Surgery

PRINCIPAL INVESTIGATOR: Thomas B. Sheridan, James Thompson,  
Mark Ottensmeyer, Jie Ren

CONTRACTING ORGANIZATION: Massachusetts Institute of Technology  
Cambridge, MA 02139

REPORT DATE: 9 Oct 95

TYPE OF REPORT: Annual



PREPARED FOR: U.S. Army Medical Research and Materiel Command  
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for public release;  
distribution unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

"Original contains color  
plates: All DTIC reproductions  
will be in black and  
white"

DTIC QUALITY INSPECTED 1

## FOREWORD

Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the U.S. Army.

( ) Where copyrighted material is quoted, permission has been obtained to use such material.

( ) Where material from documents designated for limited distribution is quoted, permission has been obtained to use the material.

(✓) Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

( ) In conducting research using animals, the investigator(s) adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council (NIH Publication No. 86-23, Revised 1985).

For the protection of human subjects, the investigator(s) have adhered to policies of applicable Federal Law 32 CFR 219 and 45 CFR 46.

( ) In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

Thomas B. Sheridan  
Principal Investigator's Signature

9 OCT 95  
Date

Accession For	
NTIS CRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

## TABLE OF CONTENTS

1. Introduction	1
1.1 Background and Significance	1
1.2 Telesurgery	1
1.3 Cooperative Manipulation	2
2. First Year Project Report	3
2.1 Human-In-The-Loop Experimental Telesurgery Simulation	3
2.1.1 Teleoperator System	3
2.1.2 Telesurgery Tool	3
2.1.3 Telesurgery Tool Handle	7
2.1.4 Laparoscopy Trainer	8
2.1.5 CCD Laparoscope and Video System	10
2.1.6 Computer Support	11
2.2 Coping With Time Delay for the Telesurgery System	11
2.2.1 Instability of Force Reflecting Control in Teleoperation System	11
2.2.2 Approaches to Cope with Time Delay	12
2.2.3 Theory of Fuzzy Sliding Control	15
2.2.4 Supervisory Control of Telesurgery System	22
2.2.5. Preliminary Human-in-the-loop Experiments with Telesurgery under Time Delay using a Virtual Remote Environment	25
2.2.6. Preliminary Human-in-the-loop Experiments with Telesurgery under Time Delay using an Actual Remote Environment	32
2.3. Expert-Novice Cooperative Telesurgery	33
2.3.1 Development of experimental tasks	33
2.3.2 Preliminary cooperation experiment: format, results and discussion	35
2.3.3 Sample surgical task pre-test results	35

3. Plans For Second Year	37
3.1. Human-In-The-Loop Telesurgery Simulation	37
3.2. Coping With Time Delay	37
3.2.1. Passive Compensation Algorithms	37
3.2.2. Demonstration of Various Control Approaches	39
3.3. Expert-Novice Cooperative Telesurgery	39
3.3.1 No delay experiments	39
3.3.2 Time delay/remote venue experiments	40
3.3.3 Paramedic Skill Evaluation/Modelling in Cooperative Telesurgery	40
3.3.4 Data analysis and reporting	41
4. Conclusions	41
References	42
Appendix A	45

# **1. INTRODUCTION**

A national goal is the development of a telesurgical system that will assist a medical care provider (who might have limited medical care experience) in the management of a medical emergency (including surgical intervention) in a location which is remote from the hospital and the experts available there. Such an event might occur in both civilian and non-civilian situations in locations such as battlefields, natural disasters, research stations in the Antarctic, and NASA space missions among others. Our research focuses on two interrelated problems:

- 1). Cooperative manipulation between a paramedic local to the patient and a surgeon operating through a telerobot.
- 2). Coping with time delay in both audio/visual and force feedback.

## **1.1 BACKGROUND AND SIGNIFICANCE**

There are many situations where an acutely and/or critically ill patient needs to be stabilized and cared for during the triage and transport to a medical center. In the optimal case, the initial care of the patient would be performed by a physician who would be riding in an ambulance enroute to a hospital. However, necessary care in remote locations might have to be provided by individuals who have minimal or no patient management skills. Normally under such circumstances no major diagnostic or therapeutic interventions are advisable during the initial triage at the accident site, nor during the subsequent transport to the major medical center. We are proposing a telemedical acute care consultant system that addresses this problem in an effort to improve patient morbidity and mortality in these clinically suboptimal situations.

## **1.2 TELESURGERY**

A telediagnostic communications link consists of a (ideally two way) closed-circuit video system, where the medical care consultant can pan/tilt/zoom a remote camera to observe the patient on a video monitor (and ideally also observe the local medical care provider who is with the patient) and converse over a synchronized audio link. An augmented system allows the physician to remotely position surgical instruments, receive tactile and kinesthetic feedback, and, with the manipulative assistance of the local provider, perform diagnostic and preliminary surgical intervention on the patient.

The type of telesurgical link used is dependent on the communication links available at the site. Alternatives include ISDN (0.128 megabits/sec), fractional T1 (0.384

megabits/sec), T1 (1.544 megabits/sec), T3 (45 megabits/sec), satellite transmission, and microwave link.

There are various barriers to implementation of telemedical systems. Foremost is the issue of liability for the surgeon, the paramedic, and the manufacturer of the equipment. There is the high communication cost associated with long distance telecommunication rates or satellite time, in addition to the initial costs of improving outdated equipment and phone lines. And in most cases, there are no standards of care or reimbursement mechanisms in place for the telesurgical services.

### 1.3 COOPERATIVE MANIPULATION

We define cooperative manipulation to be the physical manipulation of the patient mediated by audio-visual communication and control through interaction between individuals working toward a common objective. Three parameters are important in cooperative manipulation: communication, manipulation, and objective.

In our project the parameters are:

**Communication:** Because our interaction will be between a paramedic local to the site and a surgeon at a remote medical center, communication will be via an audio-video link which will have some amount of time delay. If the distances are large and especially if satellite communication is used that delay has a significant effect on control stability.

**Manipulation:** The diagnostic and therapeutic tools that will be used are the DPL cannula, laparoscopic surgiports, laparoscope, and laparoscopic tools (forceps, shears, blunt probe, electrocautery, and clips).

**Objective:** The initial diagnosis and surgical treatment of trauma patients during triage and transport to the medical center.

To our knowledge, no one has previously studied the interaction between a human and telemanipulator controlled by another human remote to the site.



## **2. FIRST YEAR PROGRESS REPORT**

### **2.1 HUMAN-IN-THE-LOOP EXPERIMENTAL TELESURGERY SIMULATION**

To support the experiments in laparoscopic telesurgery, we make use of a teleoperator system, a laparoscopic surgical trainer, various surgical tools, and supporting computer hardware. Fig. 2.1 shows the system configuration including the human participants and the major apparatus components. The apparatus is described in the following sections.

#### **2.1.1 Teleoperator system:**

The master-slave system that we use is composed of a pair of PHANTOM haptic feedback arms. These arms, originally designed for use individually in providing haptic feedback for virtual environments, are ideal in a bi-lateral force-reflecting teleoperator system because of their high bandwidth in both position control and force feedback, because of their size and because the kinematics of each arm are identical. The arms (Figs. 2.2a, 2.2b) are mounted such that a user would stand with his or her shoulder under the first axis, giving full access to the range of arm motion.

At present, both arms are controlled by interface cards installed in a single Pentium PC. It is expected that in later experiments, the cards will be installed in separate Pentiums linked by ethernet or some other high bandwidth communications medium. In this way, the arms will be able to be separated by arbitrary distances. To evaluate the effect of time delays on control, control signals will be buffered for set periods, then transmitted to the slave.

As supplied by SensAble Devices, the arms provide three degrees of freedom (DOF) with force feedback for endpoint translation, and a gimbal wrist with orientation measurement, but no torque feedback in the wrist DOF. For use in laparoscopy, the roll axis of a tool must also be controlled, and a further DOF is required to actuate tools like forceps or scissors. The novel motorized tool designed and built to satisfy these requirements and the tool handle to control it are described in the next sections.

#### **2.1.2 Telesurgery tool:**

The basic laparoscopy tools (e.g. dissecting and grasping forceps, scissors) have two degrees of freedom each; one to control the roll axis of the shaft, and one to control the open and close motion of the tool. The final design (Fig. 2.3) uses a 3W DC motor and a lead screw mechanism to drive the gripper motion and a .75 W DC motor to drive a pinion-gear pair for the roll axis. Position measurement is achieved through optical encoders

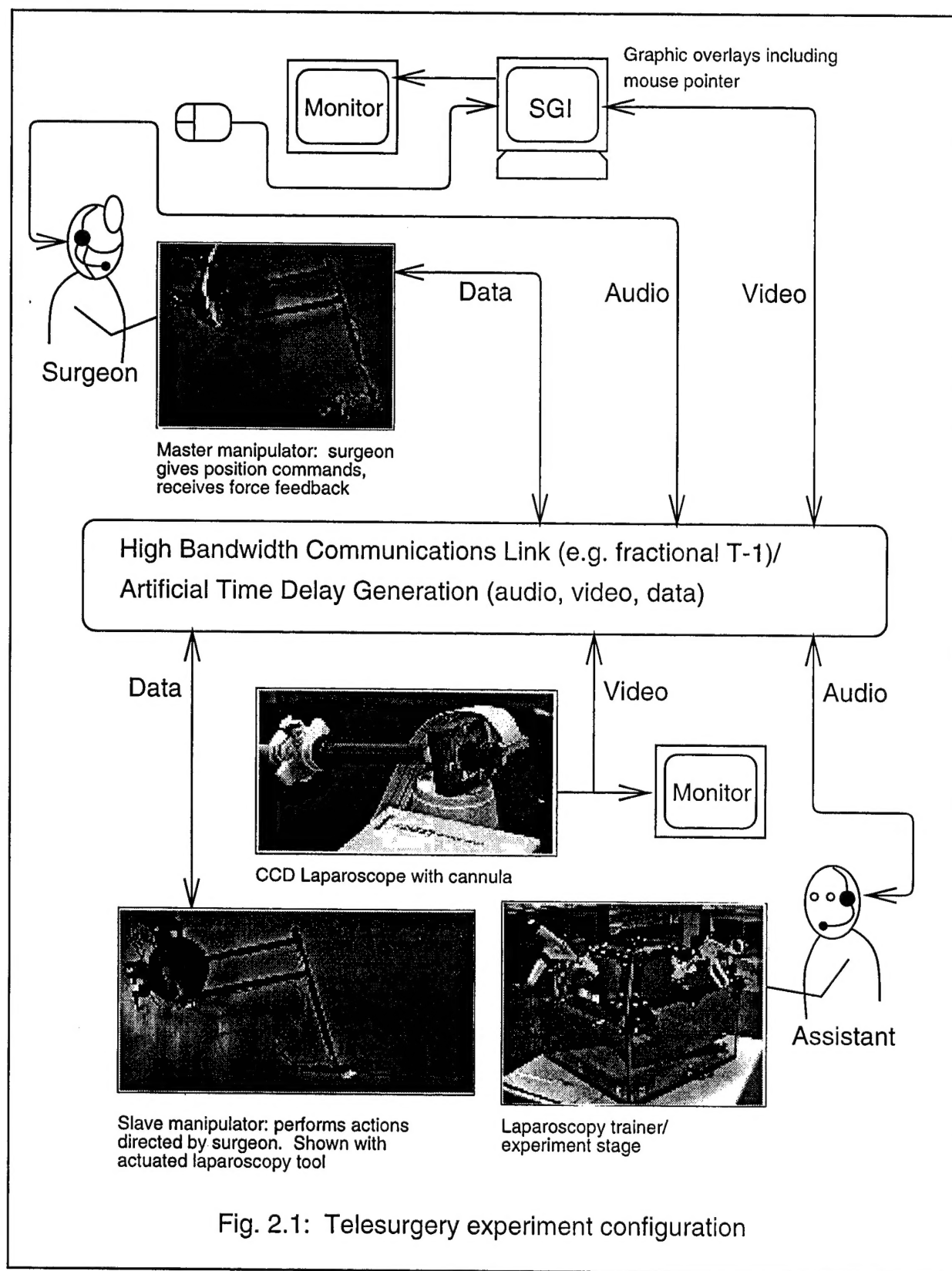




Fig. 2.2a: Master Manipulator



Fig. 2.2b: Slave Manipulator

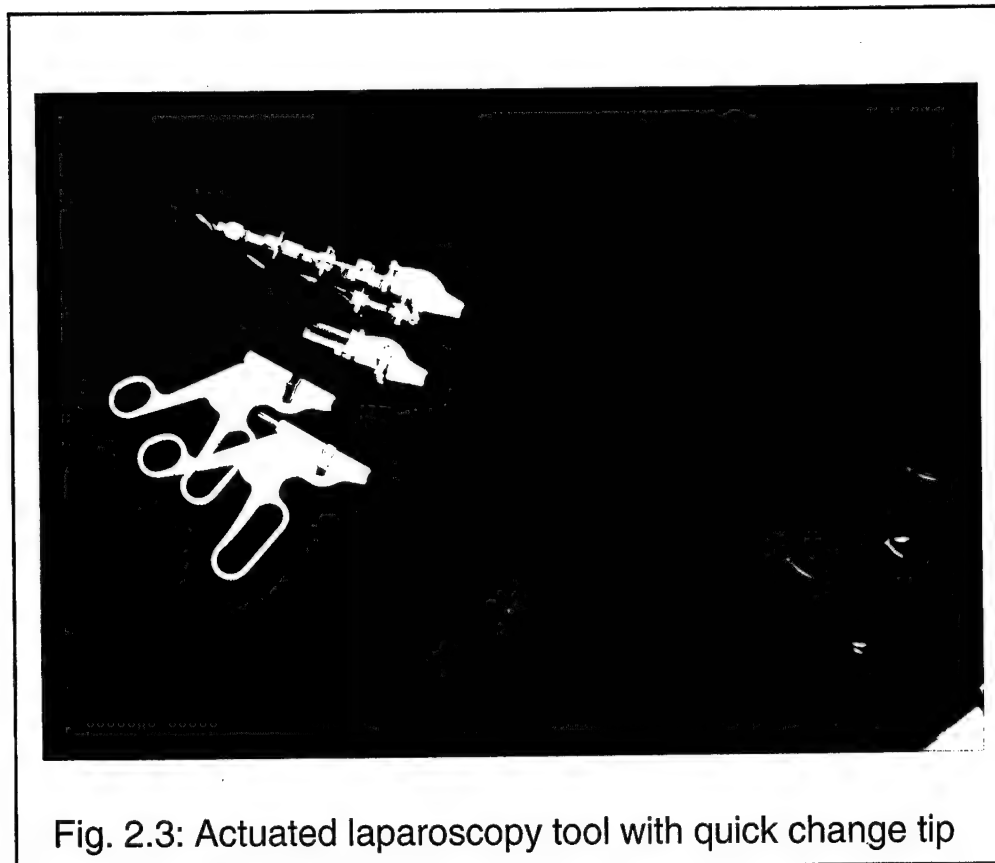


Fig. 2.3: Actuated laparoscopy tool with quick change tip

mounted to the motors themselves. Rather than designing entirely new tools, the shafts and tool tips from laparoscopy tools manufactured by AutoSuture were modified so they could be driven by this system. The axial force required for the scissor tool (the highest for all the tools tested) is on the order of 30N, higher than the limit for the motor, so thrust bearings just forward of the 3W motor gearhead are used to carry the load.

The tool shafts themselves are interchangeable so the drive portion of the tool can be used with different tool tips. Total mass is approximately 220g (approx. 8oz). While this is higher than a normal unmodified tool (50-100g/2-4oz), it is not unreasonably so, and the extra weight can be compensated for in the controller.

Preliminary tests show that the tool performs as designed, being able to cut through suture material or several thickness of paper and grasp and hold objects firmly.

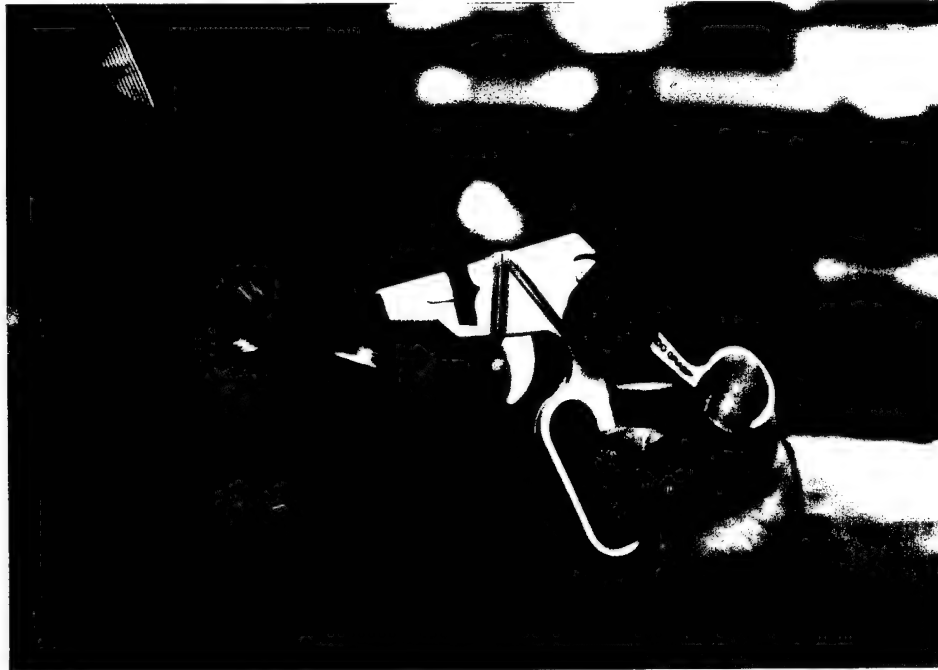


Fig. 2.4: Tool handle

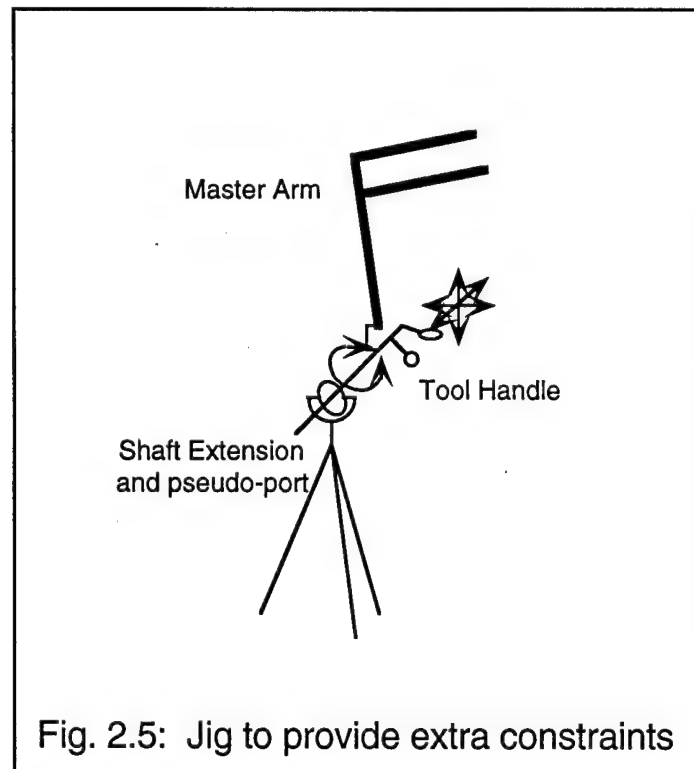
### 2.1.3 Telesurgery tool handle:

The tool handle is a modified EndoGrasp handle. A short length of the original shaft is mounted to an encoder to provide roll axis measurements, and another encoder is mounted on one side to measure the scissor motion (Fig. 2.4).

The EndoGrasp handle was chosen because it also has a trigger which can be instrumented in the future if additional inputs are required.

At present, the tool handle does not provide force feedback for either the roll motion or the gripper. However, since laparoscopic surgeons currently depend almost entirely on visual feedback, this is not seen as a major disadvantage. A more serious disadvantage was recognized during design: without torque feedback to the master, the handle can be oriented in directions other than those corresponding with the slave tool axis. This might cause confusion for the surgeon. To alleviate this problem without the necessity of providing full 6 DOF force feedback, a rod will be attached to the master where a normal tool shaft would be, which will pass through a cannula mounted in the same position relative to the master as the real working cannula is to the slave (Fig. 2.5). In this way

surgeon will be subject to the same constraints as the tool. Given that most feedback in laparoscopy is visual, minor discrepancies in the directions of force feedback due to slight misalignments of the cannula should not be distracting to the surgeon.



#### 2.1.4 Laparoscopy trainer:

The trainer (Fig. 2.6) provides a stage on which to perform our experiments. It includes typical features found in basic commercial trainers: an opaque cover to block direct vision, a number of ports through which cannulae and surgical instruments can be inserted and a stage to attach test apparatus. The walls of the trainer are transparent Lexan, so an external video camera can record tests from a fixed viewpoint. The top is a frame of acrylic strips holding pieces of 1/8" sheet neoprene. It was found that the neoprene has a tendency to tear if a cannula inserted directly through it is moved even small amounts, so the ports cut into the rubber are covered with four layers of (0.5 mm) latex rubber, which does not tear when the cannulae are moved. The trainer is approximately 15x15"x10" high.

A Polhemus 6-d.o.f. position sensor can be used inside the trainer. The magnetic field emitter unit is mounted underneath the stage, and the sensor can be attached to the laparoscope, various tools, or a dedicated probe (modified clip applier) (Fig. 2.7). This device will allow tracking of tool positions within the trainer in case these data are needed.

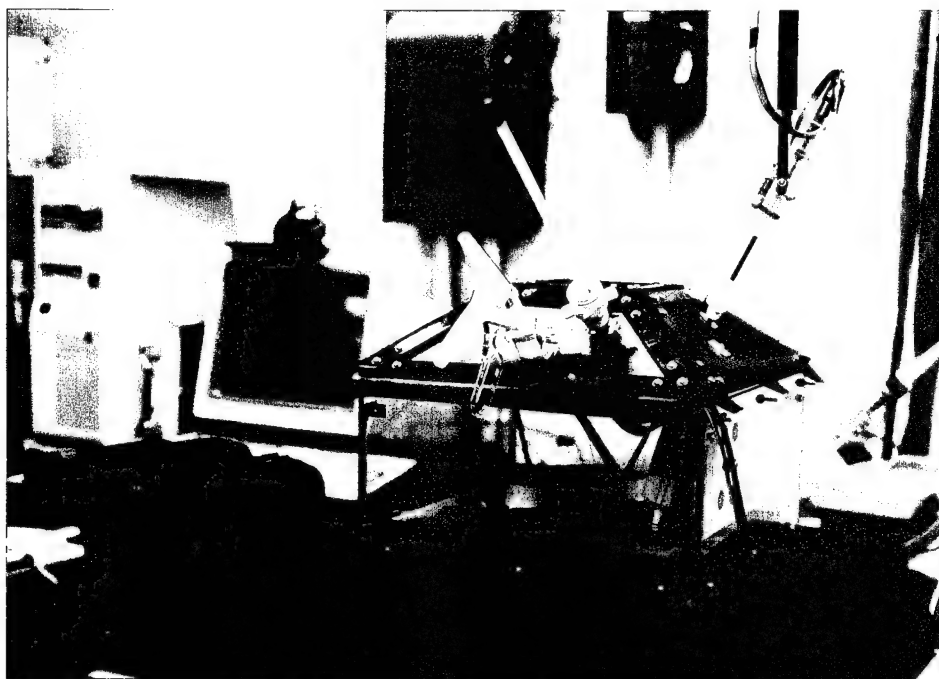


Fig. 2.6: Laparoscopy Trainer

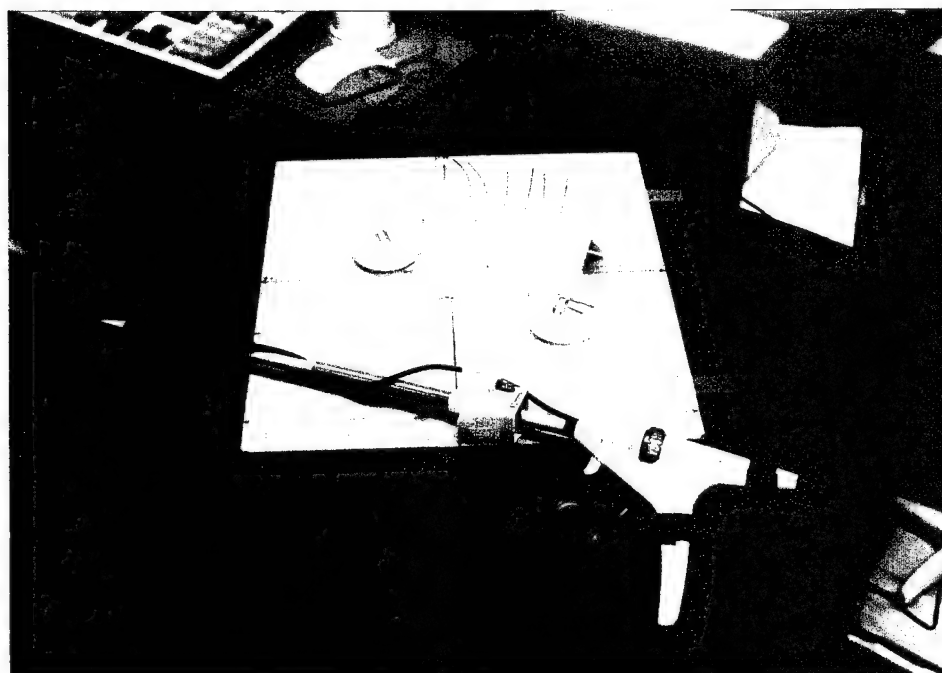


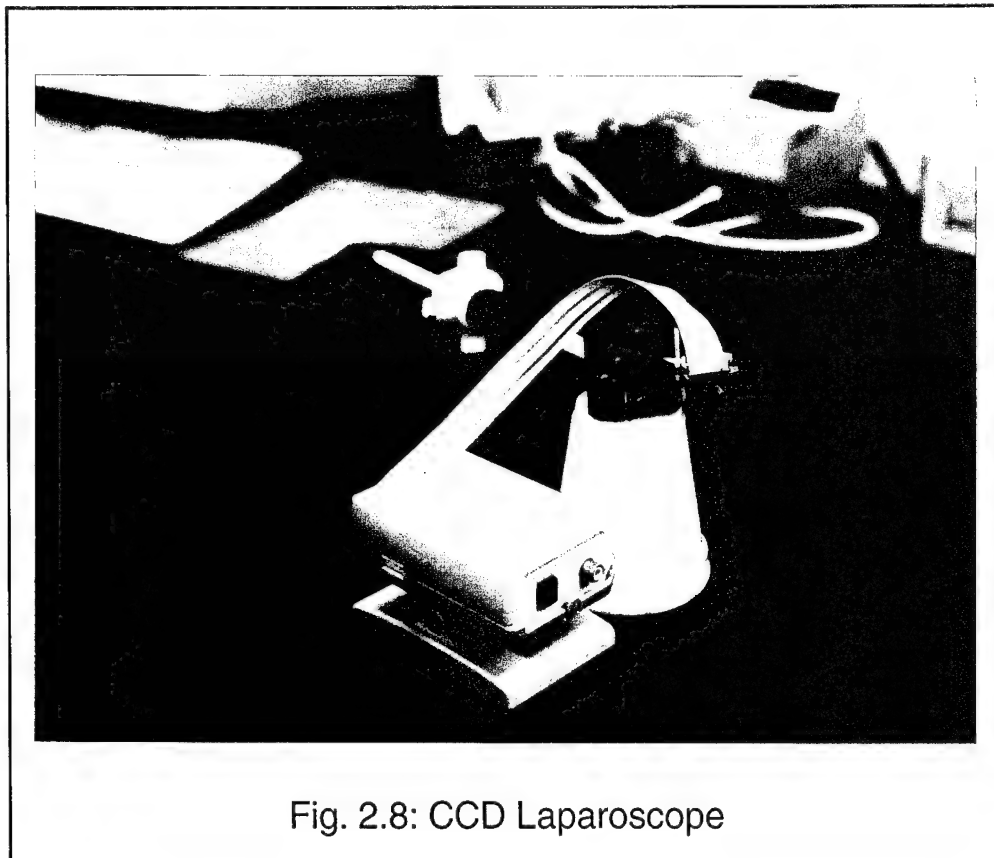
Fig. 2.7: Experimental Stage. Shows Polhemus probe, apparatus for laparoscopy training tasks

### 2.1.5 CCD laparoscope and video system:

Surgeons receive visual feedback in laparoscopy through the use of a laparoscope. It is a tube, 10-11mm in diameter, containing fiber optic bundles to transmit light to the operative site and the image back to an externally mounted video camera. In our experiments it will not be necessary to insert or remove the laparoscope, so a simpler device without fiber optics was constructed to serve in its place.

A desktop video camera was modified and the CCD was mounted to a 5/16" acrylic rod. An extension cable was constructed to connect the CCD to its supporting circuitry. The rod will be able to be attached to the motorized tool to control its rotation (Fig. 2.8).

While it is a fixed focus device, the camera has a small aperature so the depth of field in focus, which has been set to approximately 2-8" from the lens, is sufficient for these experiments. The camera produces a color image with a resolution of 330 horizontal lines by 350 vertical. The main circuit board for the camera is mounted inside the laparoscopy trainer, and is connected to the CCD by a 16" ribbon cable.





Currently, video output is sent through an SGI Indigo<sup>2</sup> workstation to a 20" video monitor seen by both participants. In the delay experiments, the surgeon will have a separate monitor which receives a delayed signal through an audio/video delay device. This artificial delay emulates the expected communication delay in a real system. Recording can be done from two points of view with the use of our lab VCR and camcorder.

#### **2.1.6 Computer support:**

In addition to the Pentium PC running the PHANTOM arms, we are using an SGI Indigo<sup>2</sup> workstation to provide support for the video/graphics presented to the surgeon and assistant and another PC (486) to sample input from the Polhemus sensor.

The SGI has a Galileo video/graphics card installed which provides the ability to combine graphic images with the video input from the laparoscope or other video camera. This gives the surgeon access to one extra "tool" in addition to the teleoperated one--the mouse pointer, which will allow the surgeon to indicate positions in the field of view in an analog fashion, rather than describing the positions verbally to the assistant.

The three machines are currently linked together through an ethernet LAN. There is an internet node and an ISDN phone line in our lab, giving us two immediate options for the communications mode to be used in the remote experiments and demonstrations.

## **2.2. COPING WITH TIME DELAY FOR THE TELESURGERY SYSTEM**

### **2.2.1. Instability of Force Reflecting Control in Teleoperation System:**

Several successful demonstrations of remotely controlled endoscopic surgery and laparoscopic surgery have taken place recently (Rininsland, 1993; Partin, 1995). However, in these demonstrations there was no appreciable time delay between the surgeon's actions and the resulting change in the endoscopic/ laparoscopic image or between the surgeon's actions and the force feedback. With increasing distance in the telesurgery task, time delay will become a problem and without special compensation, will produce instability, making telesurgery impossible. Communication of information over long distance involves time delays associated with sequential shift register operations as well as the transmission of radio signals through space. In the case of telesurgery, (particularly where satellites are used) these delays appear both in the transmission of commands to the remote surgical system and in the feedback of information to the surgeon. Among all the effects of time delays, such as image transmission, control signal transmission, sensing information

feedback, and so on, force reflection is dominantly important to perform telesurgery practically. The latter is true because a human can ignore visual time delays of a small fraction of a second, but those in a force loop inherently close the loop through the control handle and cannot be suppressed by the human operator without holding the control handle rigid.

The force reflecting control of a teleoperation system with large time delay (more than 0.2 second) is unstable (Bejczy,1994). Usually the communication time delay is in order of 1 second if satellite communication is used (Sheridan,1989). In that case, the delayed forces imposed on the operator's (surgeon's) hand will be significantly out-of-phase with his or her intended motions, and will therefore excite instability in the teleoperation system and make teleoperation or telesurgery very difficult to implement. From a control system point of view, large time delay generates a large phase lag in the system loop, decreasing the phase margin of the system significantly and making the system unstable. It is very difficult to design compensator for such a delay (Niemeyer & Slotine,1991). Therefore, the classic controller, such as proportional-plus-derivative (PD) control can not make the teleoperation system with large time delay stable unless some way can be found to change the system's physical parameters. Fig. 2.9 shows a typical dynamic response of a teleoperation system under force reflecting control when the end point of the slave manipulator contacts the surface of an object. The instability in this operation is shown clearly in the dynamic response.

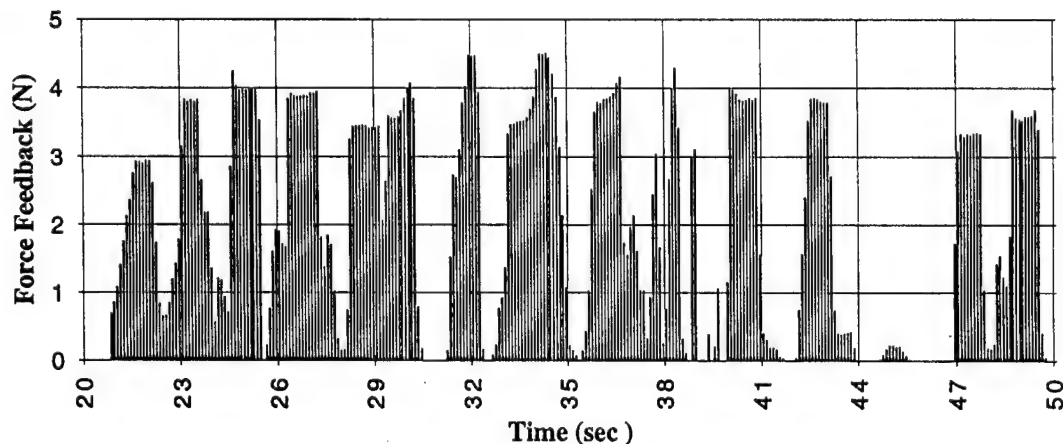


Fig. 2.9 Typical Dynamic Response of Force Reflecting

### 2.2.2. Approaches to Cope with Time Delay:

A conceptual diagram of a master-slave system for telesurgery is shown in Fig. 2.10. Generally speaking, in a telesurgery system, there are a master manipulator and a slave manipulator, which together comprise a master-slave manipulation system. To implement

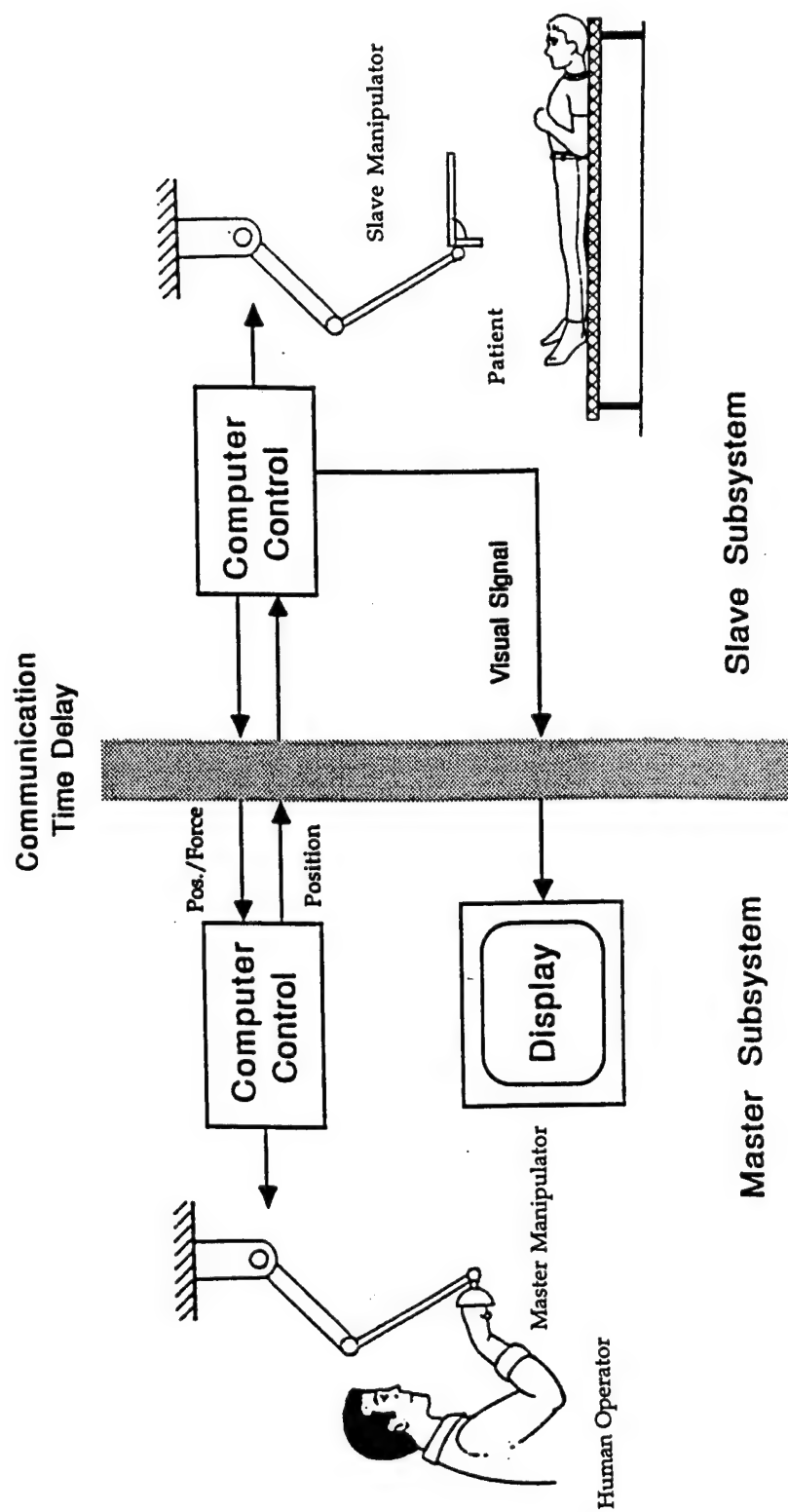


Fig 2.10 Conceptual Diagram of Master-Slave Systems

telesurgery, a human operator (surgeon) performs his/her task for the patient by means of the master-slave system through a long distance communication link. This may result in a significant communication time delay between the master manipulator and slave manipulator. The slave manipulator must be equipped with surgical tools to perform the operation, and the master manipulator must have a versatile tool handle to let the surgeon control the various tools. To pursue surgery effectively, some computer-graphic aiding of vision is necessary, including superposition of target and predictor icons on the video image.

Several approaches to coping with time delay in telerobotics have been proposed since the 1960s. Ferrell (1966), Buzan (1989) and Buzan and Sheridan (1989) investigated the special case of delayed force feedback, and developed specialized predictors to cope with delayed force. Time delay in a teleoperation loop can also be circumvented altogether by using supervisory control, in which the telerobot is programmed to perform operations in short closed loop segments and control is managed locally through artificial sensors and computer within the task segments (Ferrell and Sheridan, 1967; Brooks, 1979; Conway et al., 1990; Funda et al., 1992; Sheridan, 1992). Hirzinger et al. (1993) demonstrated telerobotic control from the Earth to the NASA Space Shuttle for simple manipulation tasks, making use of both predictor display and supervisory control techniques. Other investigators have suggested means of artificially damping or smoothing control signals to prevent instability (Niemeyer and Slotine, 1991).

So far, the approaches proposed and investigated can be categorized into: (1) "Move and Wait"; (2) Predictor display; (3) Supervisory Control; (4) Passive Compensation. In our first year's research, we investigated approaches (1), (2), (3) on our telemanipulation system according to our schedule. Approach (4), passive compensation, will be studied on our system in the fall, 1995. Considering that a human operator is in the loop in combination with signal transmission time delay and environmental uncertainty, we proposed a new approach: "Fuzzy Sliding Control". The following sections will describe the control theory and the experimental results. Another approach, supervisory control, has been implemented in the telemanipulation system and will also be described.

To seek an appropriate approach to stable controller design, we need to simplify the model of the system first. Three important features crucial to controller design are: time delay between the master and slave system; uncertainty of the task environment; and the human operator in the force control loop. Since there is no way to change the human force reflection and the time delay in the teleoperation system, we can only model the task environment. In our research, a simple task simulating the telemanipulator interaction with the tissue of the patient's body was provided by a mechanical beam. Normal forces applied

are non-linear with both normal displacement and tangential position, much as would be encountered in surgery. This provided a good test of our methods for coping with delay. Fig. 2.11 shows the beam. Interaction with the beam can be separated into three different control modes: free motion mode, transition mode, and contact mode. Among the three control modes, the operation of free motion mode is always stable because the loads of motors are almost the same in this case. Therefore, in our research, we focus on contact mode and transition mode.

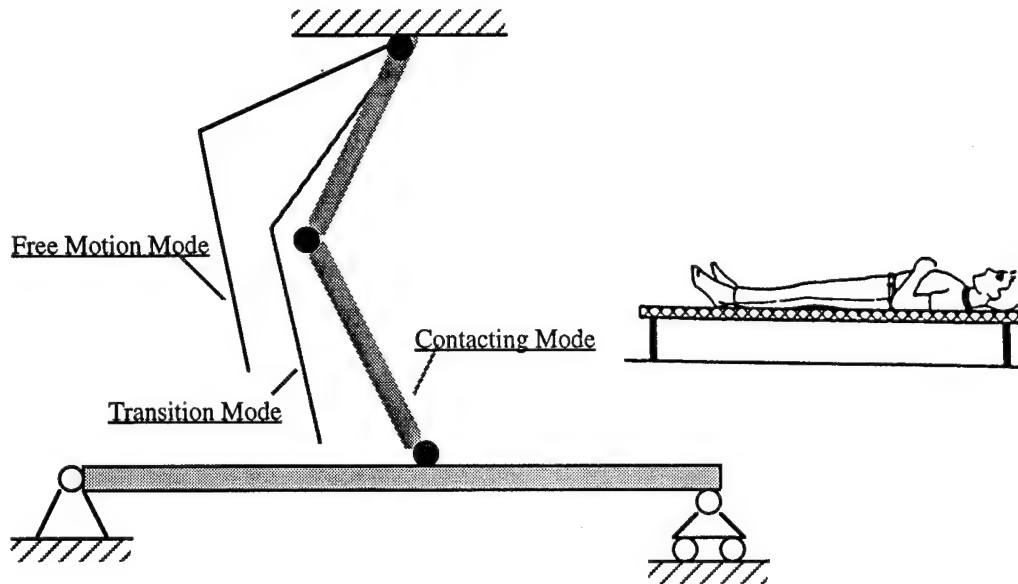


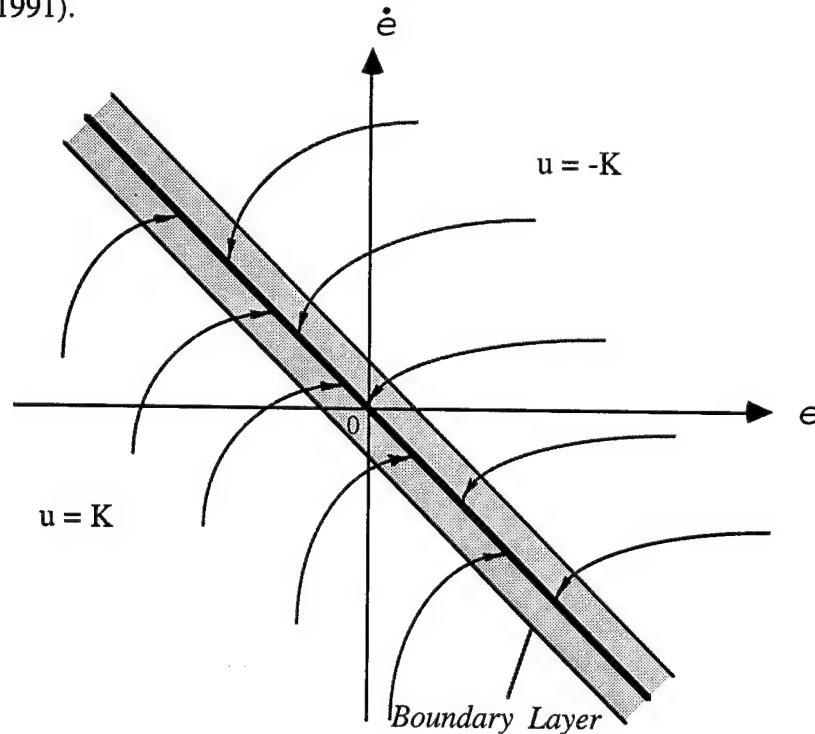
Fig. 2.11 Beam Model and Operation Modes

### 2.2.3. Theory of Fuzzy Sliding Control:

From our own trials with the “move and wait” approach to controlling with time delay, we found that the delayed forces imposed on the controlling hand perturb the system with an out-of-phase signal and therefore excite instability in the telemanipulation system. If we can apply a dead zone together with some kind of logic to the system controller, we can decrease the effect of perturbation of the delayed force feedback, and thus can improve the stability of telemanipulation. To the dead zone we added fuzzy control. Combining with the sliding control principle, a new approach we call Fuzzy Sliding Control is proposed. The advantages of this combination are given below.

Why sliding control (with deadzone) and fuzzy control? Fig. 2.12 illustrates the sliding control principle, basically a nonlinear switching control strategy. By predefining the switching surface and a dead zone or boundary layer along the switching surface, the control law can be chosen so that any control state in the phase plane can automatically

reach the boundary layer. Within the boundary layer, the control state can be tuned such that it reaches the switching surface without overshoot. Then along the switching surface the control state converges to the origin. This allows for acceptable control yet prevents oscillation. Sliding control is absolutely stable according to the Lyapunov Stability Principle (Slotine, 1991).



2nd Order System:  $\ddot{x}(t) = f(x, t) + u + d(t)$

Switching Surface:  $s(x, t) = \dot{e} + \lambda \cdot e$   
 where  $e = x(t) - x_d(t)$

SMC with Boundary:  $u = -\lambda \dot{e} - K \cdot \text{sat}(s / \delta)$

$$\text{sat}(x) = \begin{cases} \text{sgn}(x) & \text{if } |x| \geq 1 \\ x & \text{if } |x| < 1 \end{cases}$$

Fig. 2.12 Principle of Sliding Control

The purpose of applying fuzzy control in teleoperation is to achieve an adjustable dead zone control, which is better than simple dead zone control because of its smooth nonlinear dead zone function. To achieve fuzzy adjustment of the width of the dead zone the rules may change with tasks, and for simplicity in implementation three rules can be chosen:

IF the perturbation magnitude is big (B) THEN the width of dead zone is big (B);

IF the perturbation magnitude is small (S) THEN the width of dead zone is small (S);

IF the perturbation magnitude is zero (Z) THEN the width of dead zone is zero (Z).

The control law (which determines the magnitude of the control signal) may also be fuzzified (Fig. 2.13). In a one dimensional case (only error input), for example, we could have fuzzy subsets Positive Small (PS), Zero (Z), and Negative Small (NS). Then we might have the following control rules:

IF the error input is Z, THEN the control output is Z;

IF the error input is PS, THEN the control output is PS;

IF the error input is NS; THEN the control output is NS;

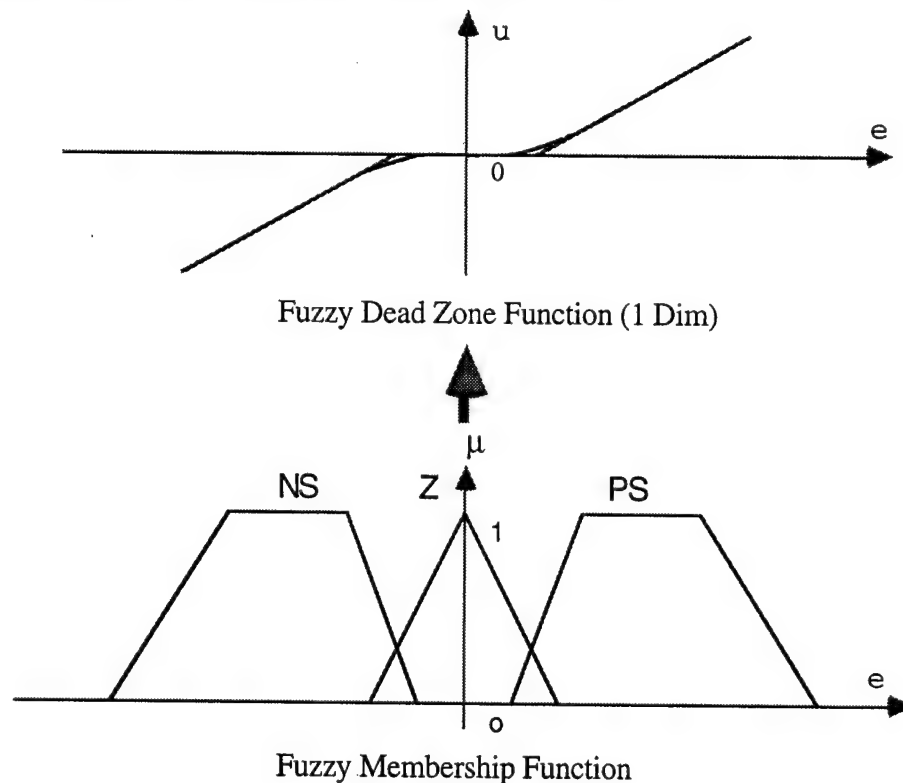


Fig. 2.13 Fuzzy Control with Dead Zone (in 1 dim.)

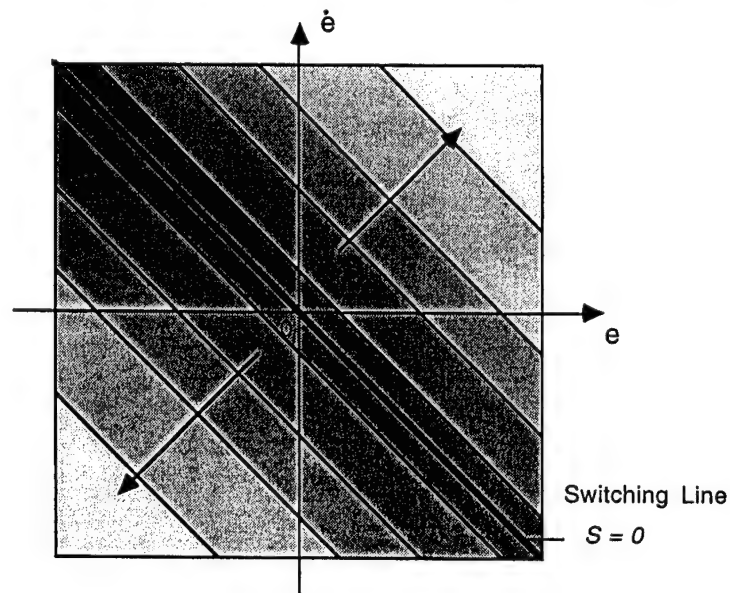
Using the above rules and procedures, the controller can provide a smooth output function. For realistic application in teleoperation, the fuzzy inference is two dimensional (i.e. two inputs: error and derivative of error) and the control rules must be designed in the

2-dimensional phase plane. Once the control rules have been chosen, it is necessary to tune the control rules in the phase plane to make them consistent. To do this, the Fuzzy Sliding Control Law has been derived based on the general sliding control principle. Figures 2.14 through 2.17 describe the fuzzy sliding control principle, the design methodology and its realization in the frame of fuzzy control system structure.

This rather *ad hoc* procedure for the controller includes the following steps:

1. Set up the preliminary control rules from intuition about the task dimensions;
2. Choose the switching line and boundary layer thickness;
3. Choose the fuzzy partitions (membership functions) of the control region and boundary layer, and those for the input variables and control variable;
4. Modify the control rules according to the Fuzzy Sliding Control Law;
5. Implement the fuzzy sliding control on the general fuzzy control system structure;
6. Simulate and evaluate the control system;
7. Re-iterate from step 2 until satisfactory responses are obtained.

Phase Plane of Fuzzy Sliding Control with Fuzzy Soft Boudary



Control Law for FSMC:

$$u = -\lambda \cdot \dot{e} - K_{fuzz}(e, \dot{e}, \lambda, \delta) \cdot \text{sat}(s / \delta)$$

$$K_{fuzz}(e, \dot{e}, \lambda, \delta) \propto |s| = |\dot{e} + \lambda \cdot e|$$

Fig. 2.14 Fuzzy Sliding Control



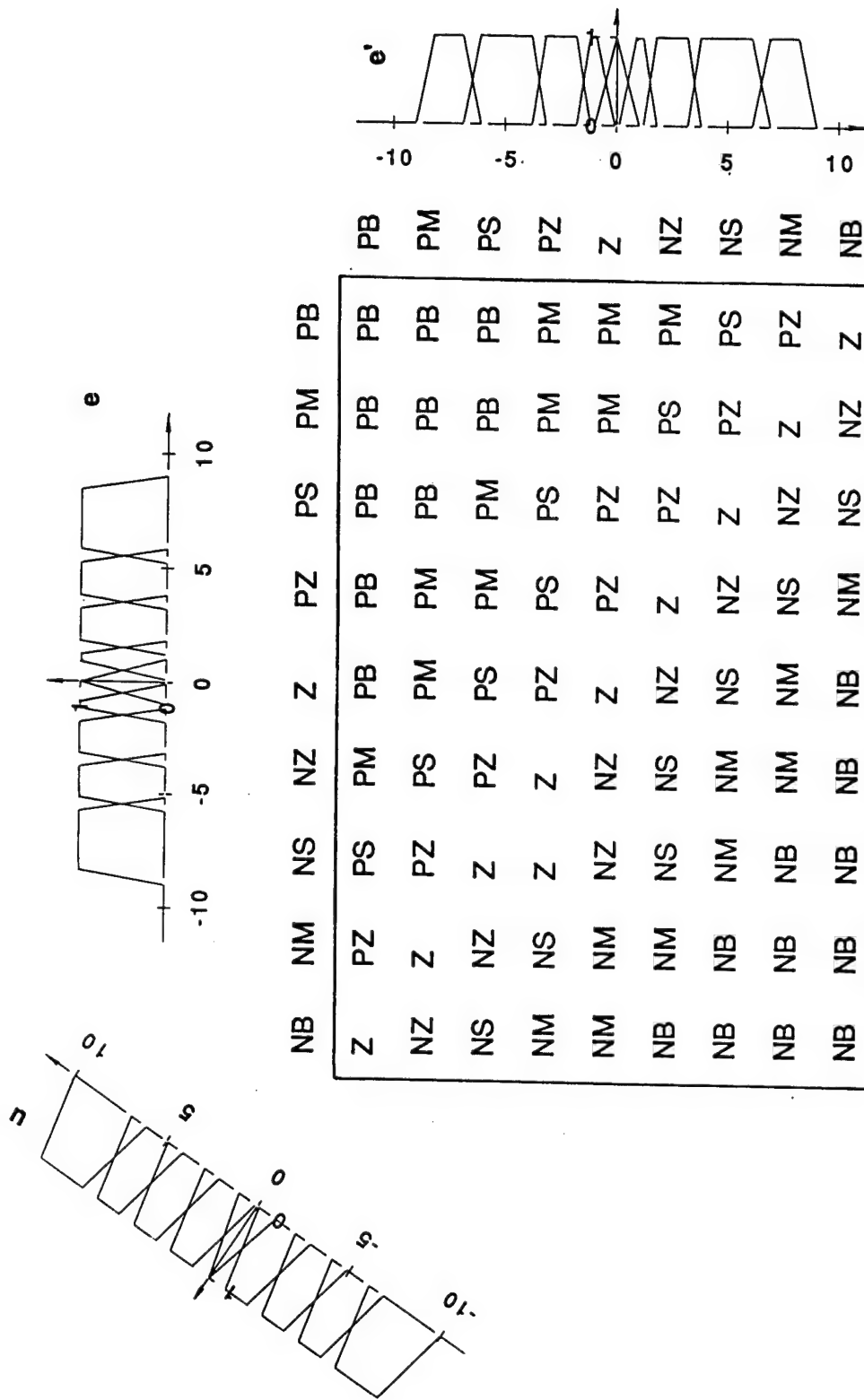


Fig. 2.15 FSC Rules in Phase Plane

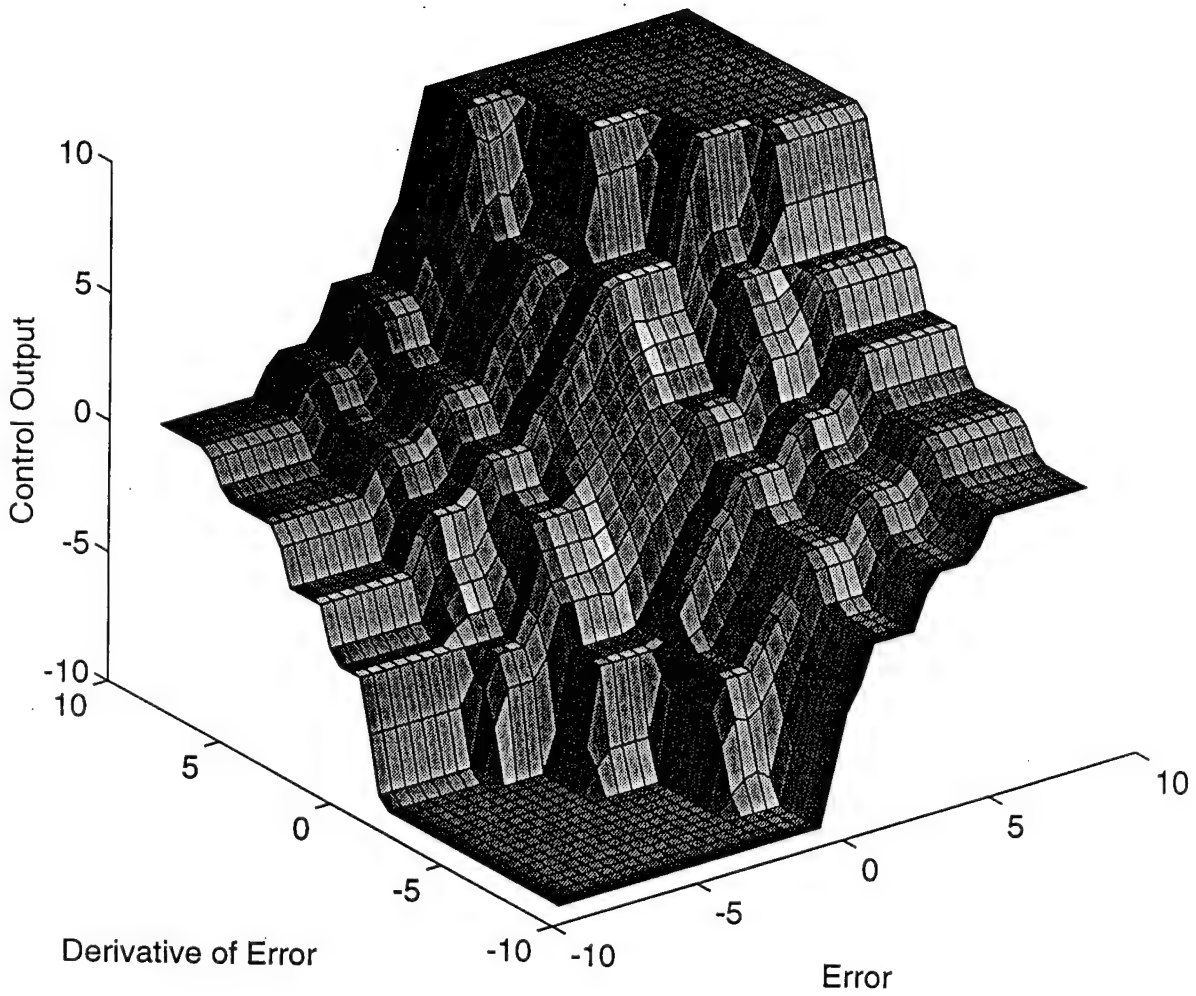


Fig. 2.16 Control Surface of FSC

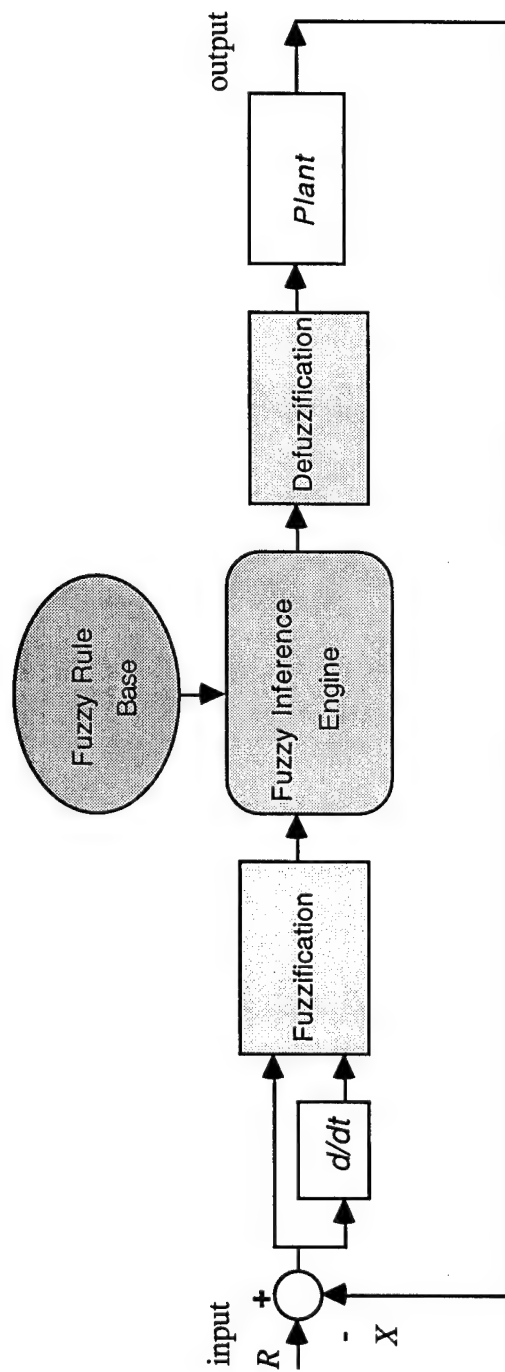


Fig. 2.17 System Structure of Fuzzy Control

#### **2.2.4. Supervisory Control of Telesurgery System:**

Supervisory control is another approach for dealing with time delay in a teleoperation system, which was initially developed in the Human-Machine Systems Laboratory at MIT in the 1960s and 1970s. Ferrell and Sheridan (1967) proposed that a hierarchical system based on a human supervisor--computer subordinate relationship could be used in teleoperation to solve some of the control problems involving time delay. Under supervisory control (Fig. 2.18) the operator sends coded instructions to the remote telerobot specifying subgoal conditions and procedures with reference to sensor states that must be satisfied. The operator's input could range from a purely manual analog command, demonstrating in time and space what is intended, to a highly abstract symbolic command made up of alphanumeric keystrokes. These instructions are sent open loop relative to the human. The remote computer then interprets the message and acts on the sensor information available to it about its own environment. In this way the control loop is closed within the remote site, where there is no time delay. The remote computer then relays that information which is deemed important and necessary for effective supervision back to the operator, the responsibility for the specific details of control being left to the subordinate computer.

The shortcomings of supervisory control with time delay are the shortcomings of the human-machine communication interface on the supervisor side. Fig. 2.19 shows our supervisory control system. There are two manipulators (master, slave), two PCs (one for master control, one for slave control), and an SGI workstation at the supervisor's interface. Force feedback is also reconstructed to aid the supervisor's operation.

As noted above, human-computer communication in supervisory control can be in terms of analog (space-time movement) language or in symbolic (alphanumeric) language, or some combination. Symbolic language is not realistic for most commands in telesurgery at the current level of technology, so we rely mostly on master-slave analog demonstration as a means for the surgeon to communicate his intentions to the computer and the human assistant. The analog commands (intended kinematic positions and movements) are displayed as computer graphics by the SGI (a virtual reality superposed on the video image of the actual patient scene) which are observable at both master and slave ends. The fact that our master and slave manipulators have identical kinematics is helpful in this regard. A computer keyboard is used to input and edit some commands. The simulated slave environment can also supply force feedback to the surgeon's (supervisor's) hand. In this way, the surgeon can both oversee the surgery operation process and feel the physical interactions. Because of the time delay, the supervisor can not intervene in the operation of

the remote slave manipulator instantly, and therefore it is important that the slave computer have an appropriate interface to the assistant who is nearby the patient. In this way the assistant can monitor the force/position control and intervene whenever necessary.

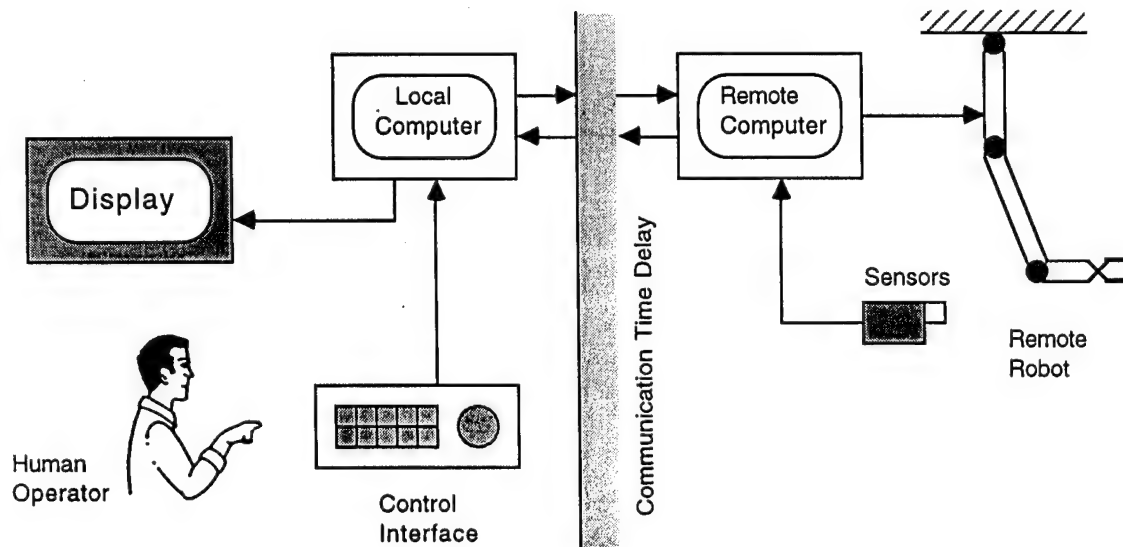


Fig. 2.18 System Structure of Supervisory Control

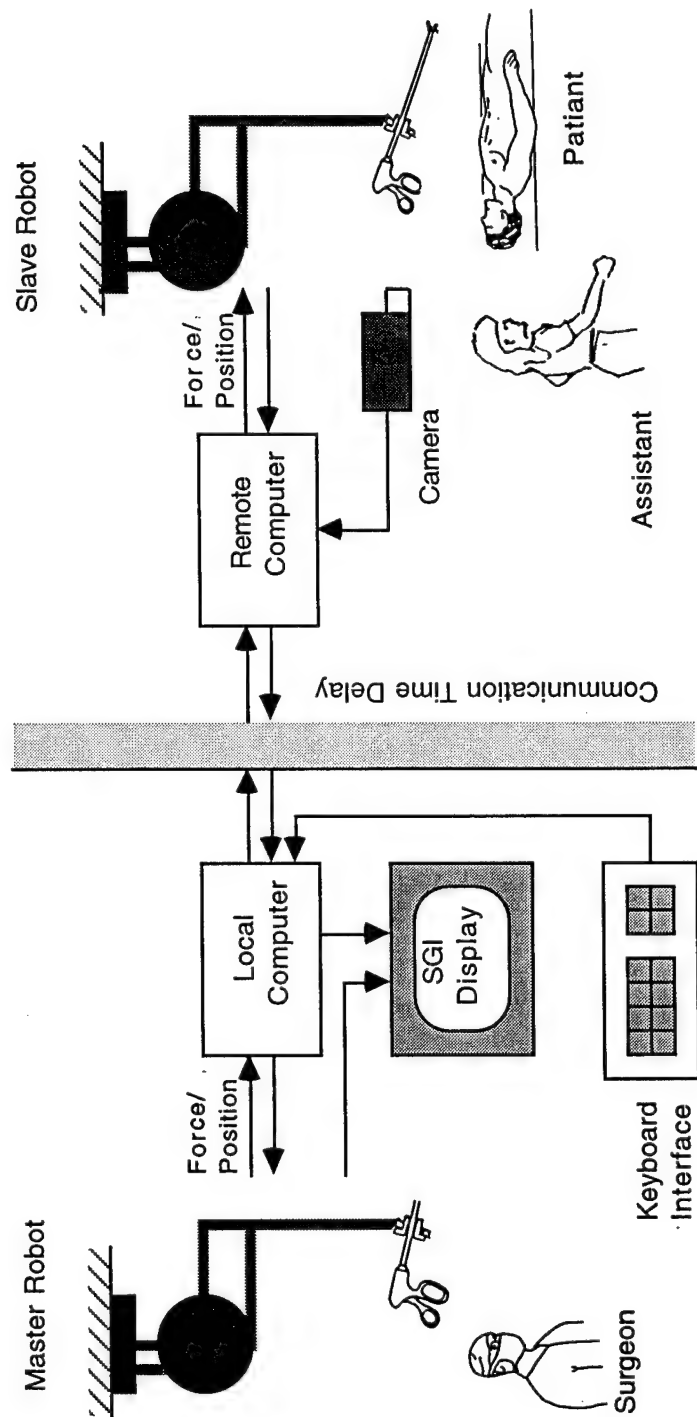


Fig. 2.19 Supervisory Control System of Telesurgery

### **2.2.5. Preliminary Human-in-the-loop Experiments with Telesurgery under Time Delay using a Virtual Remote Environment:**

For the purpose of preliminary experiments, in which we had better control over key parameters of the telerobot system, time delay and manipulation tasks, we developed a virtual slave arm (which includes dynamic simulation of the motor driving system), a virtual beam to probe, and the associated graphics displays. The task in each case was to move the real master arm so that the virtual slave arm contacted the virtual beam at a given point from a free-space starting position, apply a small force, then slide along the beam to another specified point while maintaining force contact.

Using the master-virtual slave system (Fig. 2.20), the following control techniques were studied:

- Fuzzy Sliding Control;
- Sliding control with boundary layer;
- Adaptive dead zone control;
- Traditional PD control;

Time delays of 0, 100, 200, 500, 800 and 1000 ms were tested. Dynamic data were recorded and used to do objective evaluation based on the vibration magnitude. Subjective difficulty evaluations were also made (Fig. 2.21). Vibration magnitude results are shown in Fig. 2.23. Comparisons of evaluations (both subjective and objective) of the controllers can be found in Fig. 2.22 and Fig. 2.24.

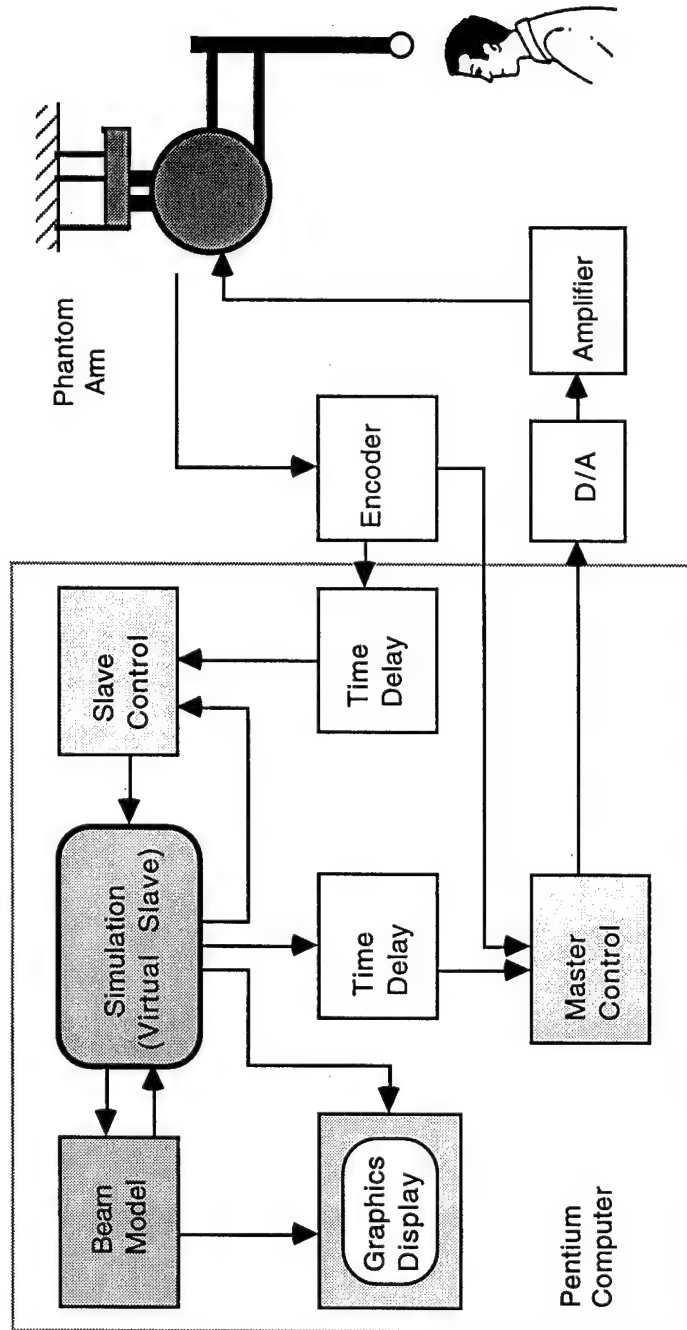


Fig. 2.20 Master-Virtual Slave Experimental System



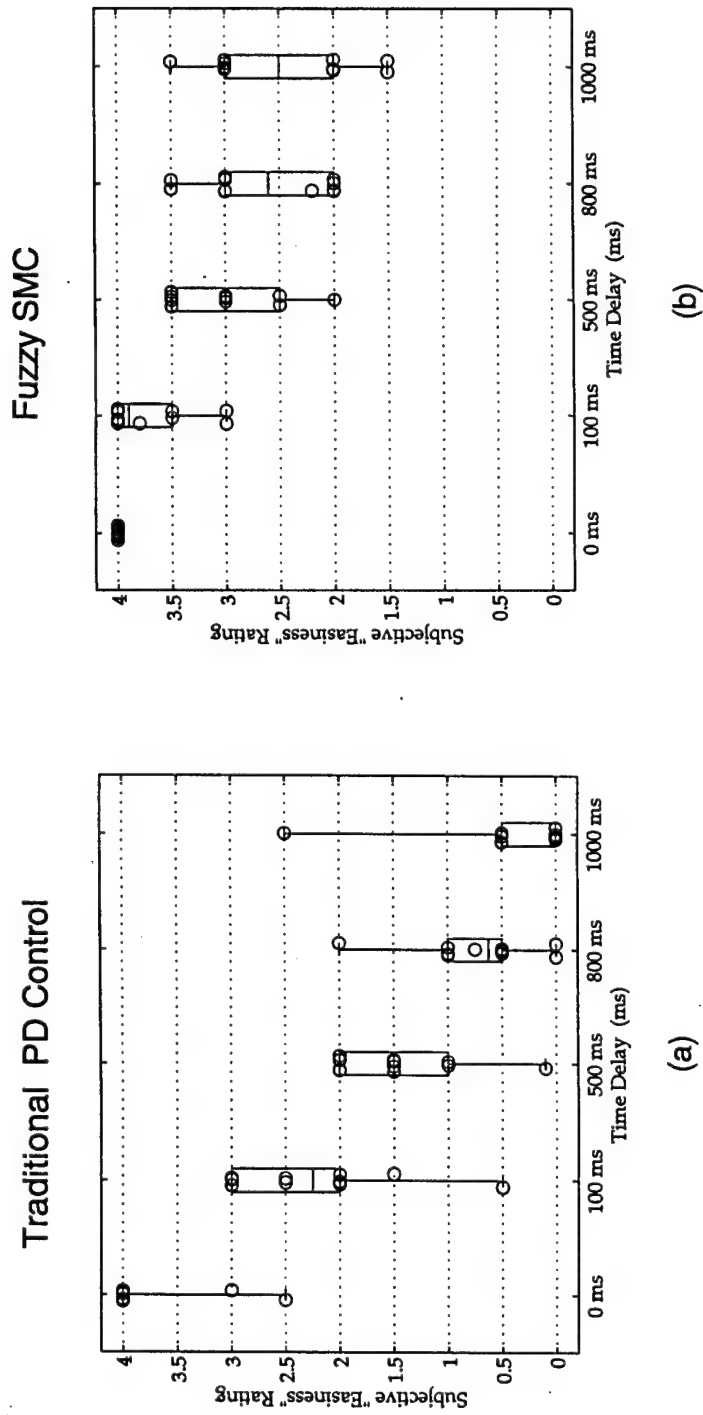
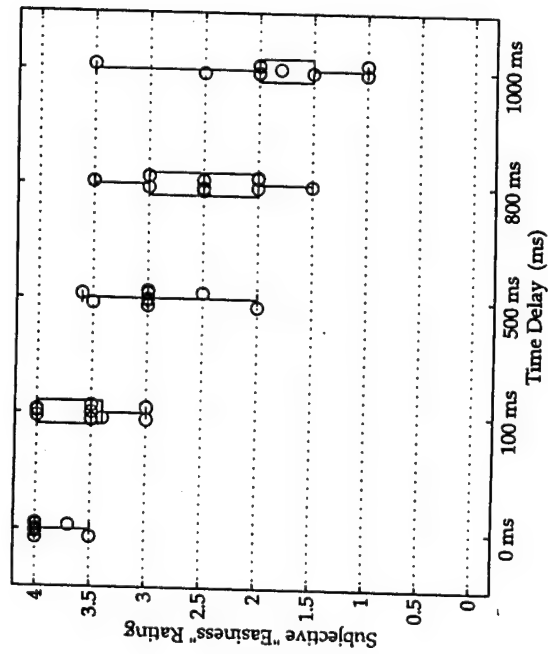


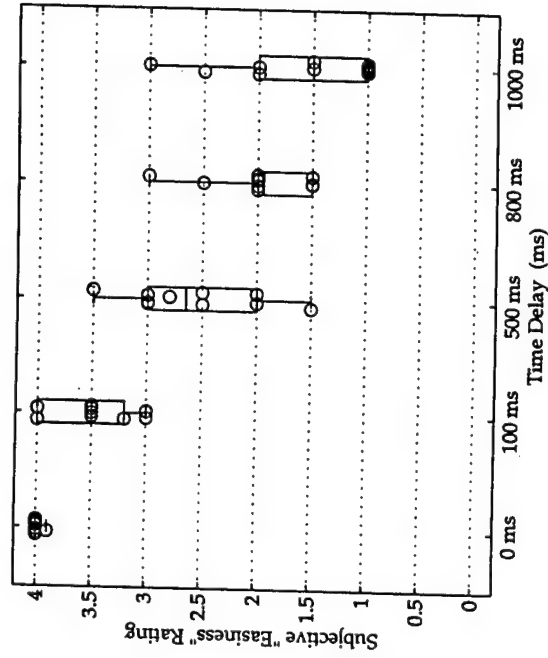
Fig. 2.21 Subjective Evaluation of Controllers with Time Delays

Sliding Mode Control w/ BL



(c)

Adaptive Dead Zone Control



(d)

Fig. 2.21 Subjective Evaluation of Controllers with Time Delays

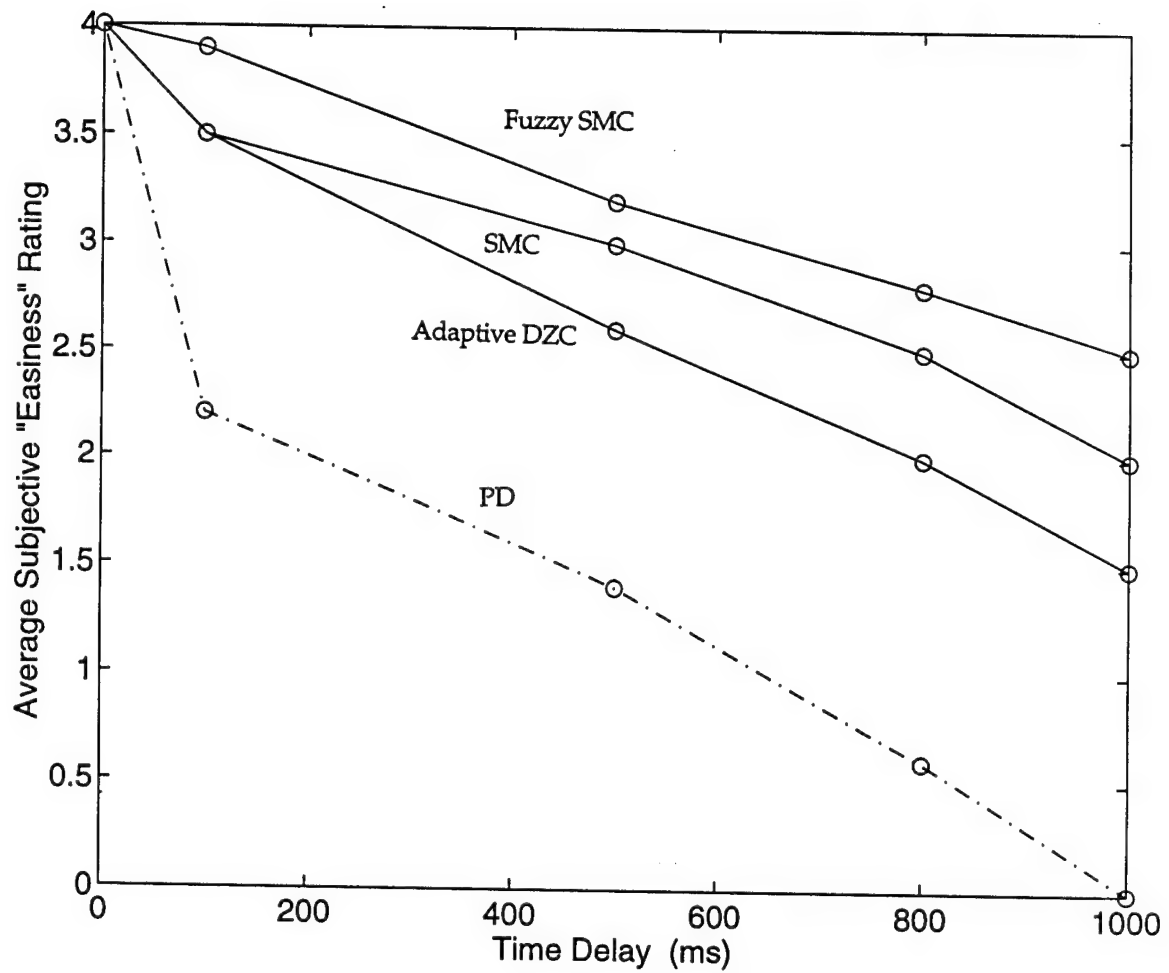
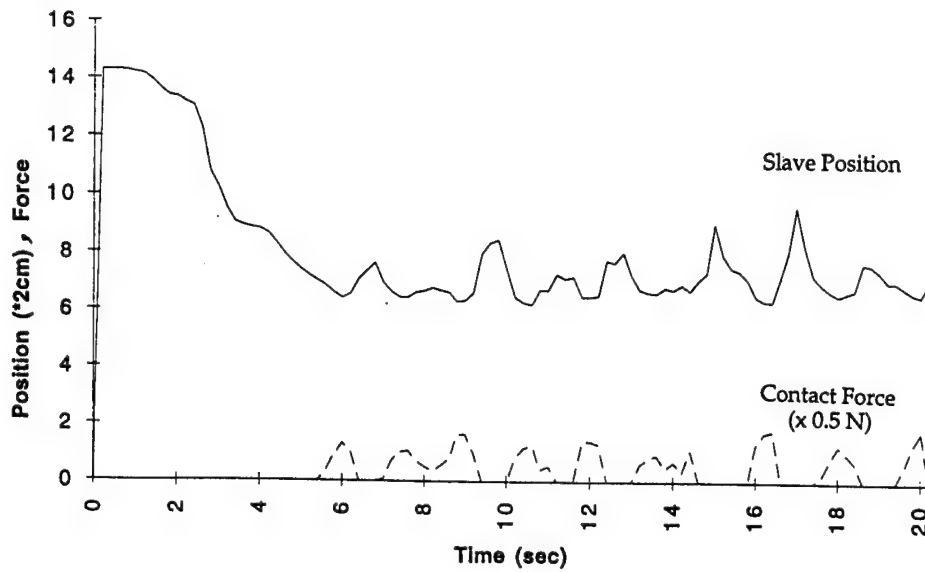


Fig. 2.22 Comparison of Subjective Evaluations

### PD Control (1 sec time delay)



### Fuzzy SMC (1 sec time delay)

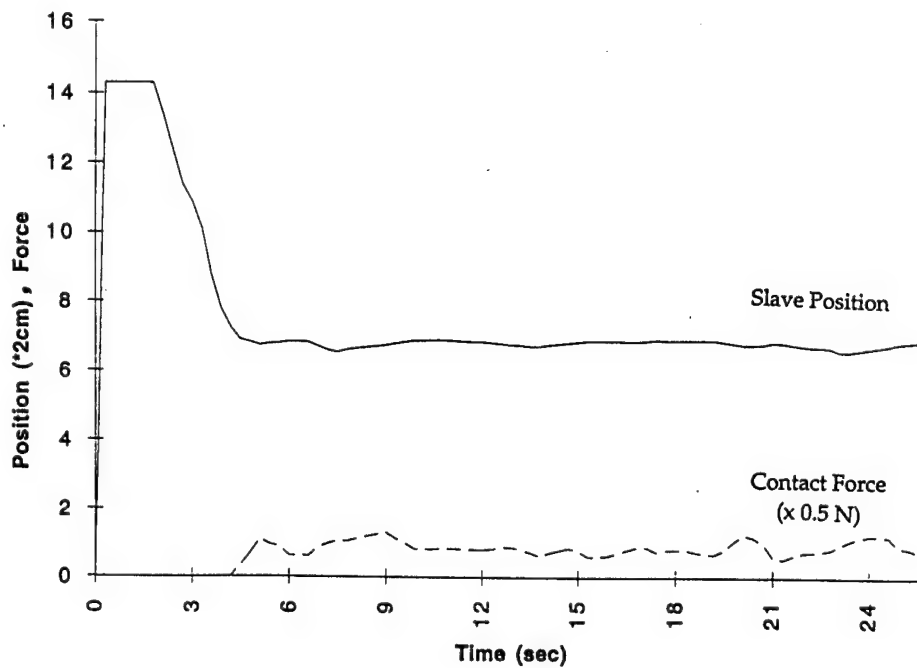


Fig. 2.23 Dynamic Responses of Teleoperation with Time Delay

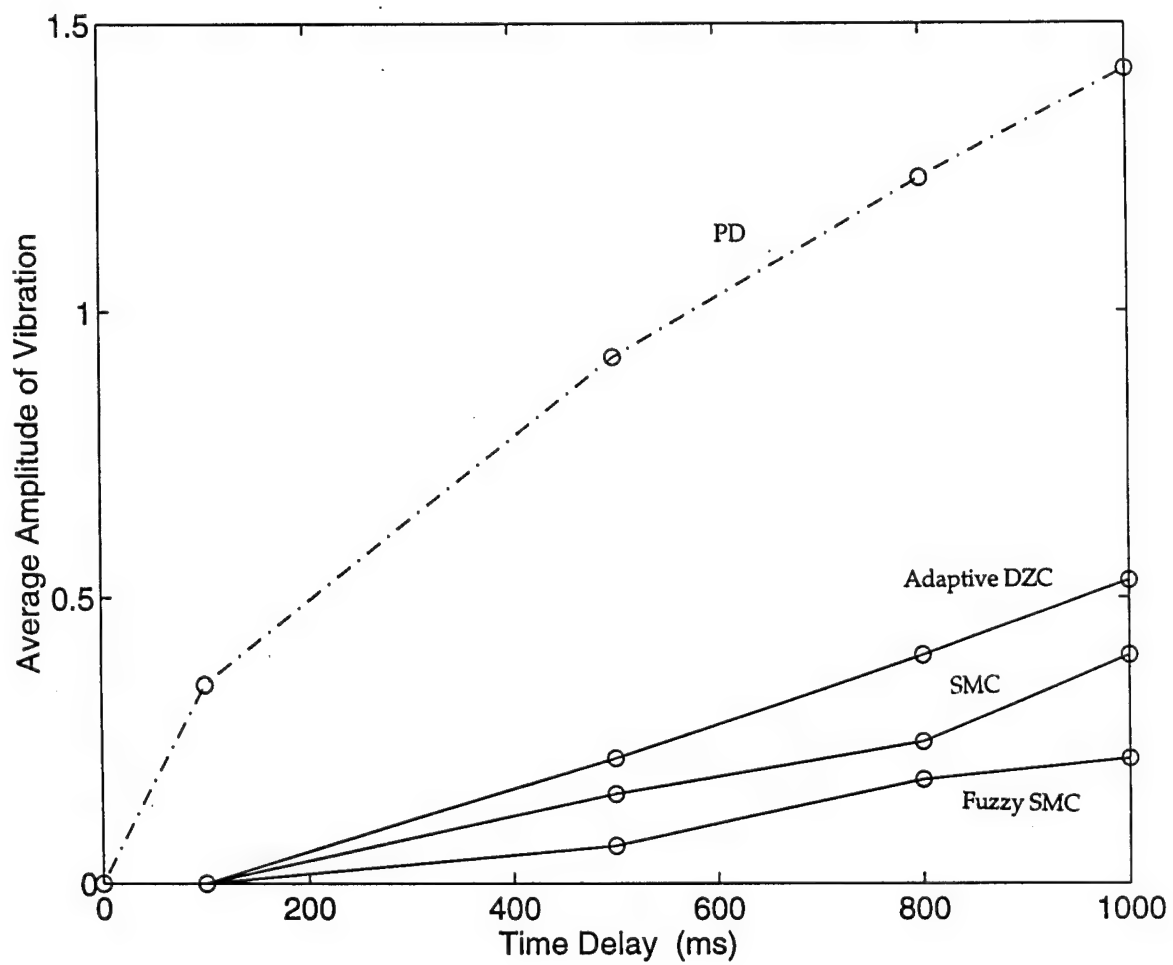
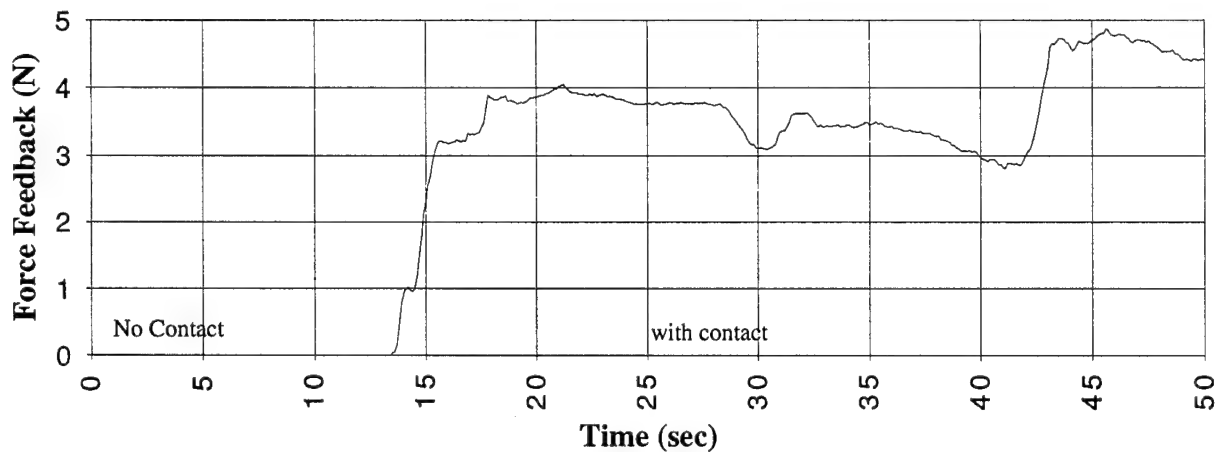


Fig. 2.24 Comparison of Objective Evaluations

### 2.2.6. Preliminary Human-in-the-loop Experiments with Telesurgery under Time Delay using an Actual Remote Environment:

After the full bilateral master-slave system was set up (Fig. 2.1), experiments were carried out by means of a real beam instrumented with strain gauges. Fig. 25 shows some dynamic responses (force feedback signals) of a typical subject experiment. The experimental results are consistent with the data obtained on the mater-virtual slave system. They show significant improvement of operator performance in the contact mode (Fuzzy Sliding Control over PD Control).

(a) FSC (1 Sec Delay)



(b) PD Control (1 sec Delay)

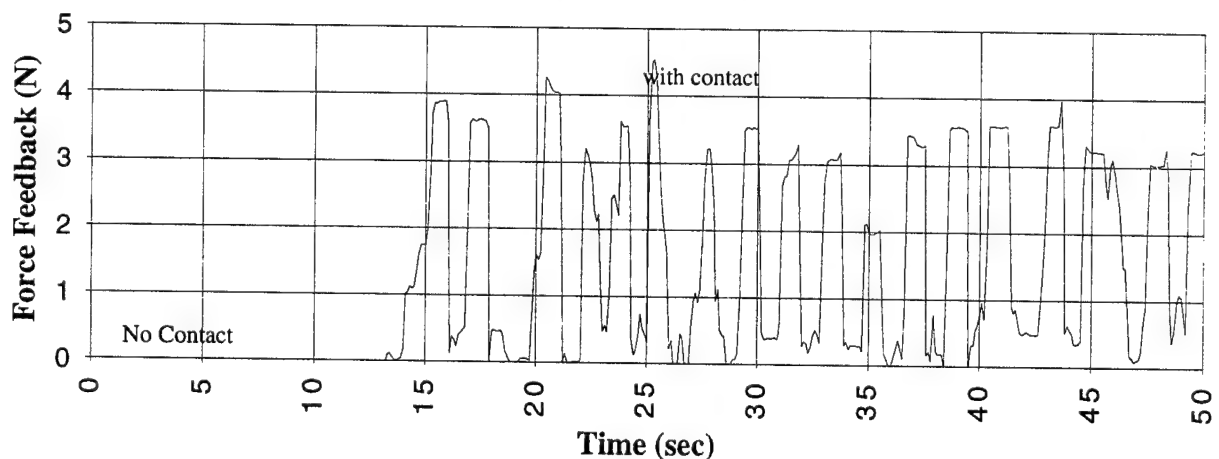


Fig. 2.25 Force Feedback of Teleoperation with 1 sec Time Delay (FSC & PD Control)

## **2.3. EXPERT-NOVICE COOPERATIVE TELESURGERY**

### **2.3.1 Development of experimental tasks:**

The challenge here is to develop credible means to evaluate various techniques of cooperative manipulation (as previously defined) in the context of telesurgery. In such research one faces the dilemma of choosing between experiments too abstract to be credible to the practitioner versus those too specific to a given task to be scientifically generalizable. Too specific a task might be using a probe simply to judge accuracy in following geometric figures. Further, at this early stage, animal and clinical trials were not options. In this project, focusing on laparoscopy provides a manageable scope within which to work and as a compromise, the experimental tasks that will be evaluated are basic training exercises used by surgeons learning laparoscopic techniques.

A set of these tasks is described by Steele, Hosking and Chung (1994). The tasks provide experience in manipulating all of the usual tools used in laparoscopy in the somewhat realistic environment of a laparoscopy trainer. The tasks include: grasping with forceps, precision motion of the tools, use of the scissors, use of laparoscopic clip appliers, various suturing techniques and a comprehensive task on animal tissue. Some of the tasks have adapted for our use and are described in table 2.1. Suturing has been omitted because as a two handed task, a surgeon cannot perform it with our system. However, with the advent of clip appliers and staplers, most of the uses of sutures can be duplicated. In addition, there is work underway to develop automatic suturing tools which require the use of only one hand (Faraz, Payandeh, Nagy, 1995).

To study different forms of interaction, in a given experimental run, the test tele-surgeon will be assigned one of the laparoscopic tools used in each task. The assistant will manipulate the others. For example, the surgeon might control the laparoscope, and direct the assistant to manipulate the other tools properly. The procedure for a full experimental run will be described later.

**Table 2.1: Elemental training tasks**

Task	Tools required	Description	Errors
Grasp & Transfer	2 grasping forceps, laparoscope	Grasp dental swab from cup 1 with forceps. Transfer to 2nd pair forceps. Place in cup 2.	Dropping swab Grasping wrong swab
G & T with Orientation*	2 grasping forceps, laparoscope	As G&T, but replace swabs with paper clips, clips must be grasped along long side, not at ends.	Dropping clip Grasping wrong clip Grasping clip at end
Precision Motion	2 grasping forceps, laparoscope	Replace clips with small folded pieces of paper. Grasp paper from cup 1. Tear along fold. Place pieces in cup 2.	Dropping paper Grasping wrong piece Incorrect tear
Use of Scissors*	scissors, grasping forceps, laparoscope	Grasp end of suture material/string with forceps. Cut beneath grasp point. Place cut piece in cup.	Cutting wrong string Dropping cut piece
Use of Clip Applier	clip applier, scissors, laparoscope	Apply 1 clip on either side of mark at middle of rubber band wrapped around cup. Cut band between clips	Incorrect placement of clips Cutting outside of clipped region of band
Animal Tissue Dissection (porcine intestine with attached mesentery)	2 dissecting forceps, clip applier, scissors, laparoscope	Separate tissue near vein from vein with forceps. Apply clips to section of vein. Cut between clips	Damaging vein Misapplying clips Incorrect cut

\* see Fig. 2.7 for apparatus



### 2.3.2 Preliminary cooperation experiment: format, results and discussion:

A simple test to evaluate the utility of cooperation between a remote expert and a local assistant was performed in the fall of 1994. (Ottensmeyer, 1995). In this test, the participants were instructed to assemble geometric puzzle pieces (Tangrams) on a table, according to a given pattern. The expert was given the pattern, and instructed the assistant in how to assemble it. The expert's mode of instruction was either verbal (symbolic) only, or symbolic with the addition of an analog device--a pointer, representing a simple teleoperator. Using this equipment, the experiment can be compared with tele-mentoring, as described by Kavoussi, et al. (1994).

What was clearly shown was that the addition of the pointer device in the communication both reduced the time required to complete the pattern by about 44% (table 2.2) and reduced the number of errors incurred in positioning the individual puzzle pieces in x and y directions by about 80%. There was no improvement in the orientation error rate (pieces in correct location but incorrect in rotation), but this is thought to be due primarily to the lack of experience of the "expert". It was noticed that with proper use of the pointer, orientation errors were virtually eliminated, but few of the "experts" learned the strategy in the course of the test.

The conclusions that one can draw from this simple test are that closer cooperation (i.e. more direct involvement of the expert) improved performance, and that with proper instruction, errors can be minimized, implying that the expert/surgeon must have extensive experience directing assistants.

**Table 2: Preliminary cooperation experiment results**

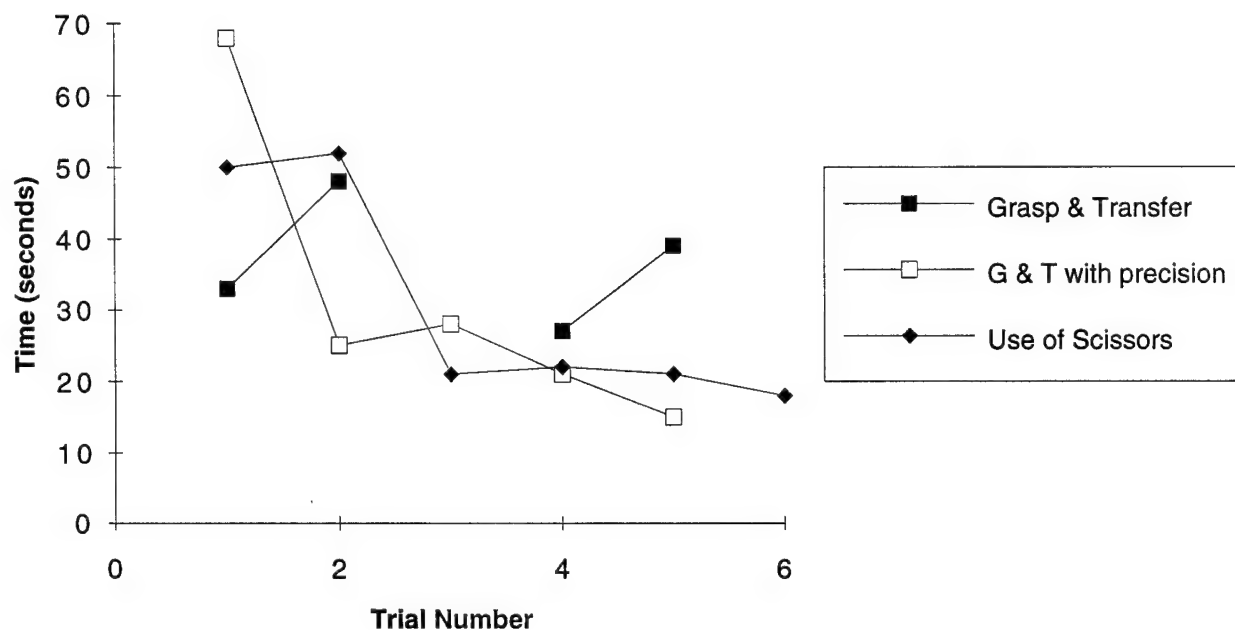
	Verbal communication only	Verbal with pointer
Completion Time	92.38 $\pm$ 30.19 sec.	52.13 $\pm$ 26.12 sec.
Position Error Rate	1.46 $\pm$ 1.16 errors/min.	0.28 $\pm$ .79 errors/min.
Orientation Error Rate	2.71 $\pm$ 1.71 errors/min.	2.90 $\pm$ 2.43 errors/min.

### 2.3.3 Sample surgical task pre-test results:

Even before the actuated laparoscopy tool was complete, it was possible to use the master-slave system to control the CCD laparoscope, so one partial set of tasks was run. This mode is similar to the clinical tests being done by Kavoussi, et al. (1994), which they call tele-mentoring. The surgeon controls the laparoscope remotely and gives instructions, but the assistant performs all of the manipulation tasks.

Fig. 2.26 shows the times required to complete each individual task in a series. Three tasks (grasp and transfer, G & T with precision, and use of scissors) were tried. In this early case both the “surgeon” and assistant were fairly in experienced. As such, no conclusions should be drawn from the data, but a cursory examination seems to indicate that the learning curve seems to fairly steep. Further discussion of the experiments and the plans for the formal tests is taken up in the next chapter.

**Fig. 2.26: Task Completion Times**



### **3. PLANS FOR SECOND YEAR**

#### **3.1. HUMAN-IN-THE-LOOP TELESURGERY SIMULATION**

Testing and demonstrating our solutions to the time delay and cooperative manipulation problems will require formally defining the Communications/Time Delay block shown in the system diagram, Fig. 2.1.

As mentioned in various sections above, achieving a variable time delay will be accomplished in two ways. The command signals between the master and slave manipulators will be buffered in either the master or slave Pentium, and transmitted after a given time has elapsed. Delay in audio and video communication will be accomplished through the use of commercial equipment designed specifically for this purpose. Equipment like this is typically used by television and radio broadcasters to prevent the transmission of inappropriate language and to ensure synchronization of signals transmitted by satellite.

To permit the transportation of either the master or slave manipulator to a site remote to the laboratory, we will either be adapting commercially available video-conferencing equipment for use with our system or making use of the internet. The video-conferencing mode combines three ISDN telephone lines to yield a 384 kbit/sec channel, sufficient to transmit good quality video and audio signals, and to carry the data requirements of the master-slave system. In theory, the bit rate through the internet is larger, but due to latencies and delays inherent in it, will likely make force feedback impractical.

#### **3.2. COPING WITH TIME DELAY**

To complete our study of the practical approaches for force reflecting control of teleoperation system thoroughly, we plan to investigate one additional approach: Passive Compensation. We will conduct further human-in-the-loop experiments to test all the approaches under different time delays, collecting both dynamic response data and subjective evaluations. We will compare the approaches to find out which is the best approach under what circumstance.

##### **3.2.1. Passive Compensation Algorithms:**

There are two similar methods for passive compensation, which are based on passive communication laws. The first method was developed by Anderson and Spong (1988) using scattering theory (Johnson, 1950). In 1990, Niemeyer and Slotine developed the second approach, the Wave Variable or Energy approach. Both methods stem from the central idea of the Scattering Theorem which derives from the fact that an analog electrical

transmission line delays the signal and is inherently passive, and any passive two-port electrical transmission line is stable. The Scattering Theorem states that a two port network is passive if and only if the norm of its scattering operator  $S$  can be defined for a two port network by the relationship between force  $f$  and velocity  $v$ ,

$$F - V = S (f + v)$$

where  $S$  is a matrix in the frequency domain.

Fig. 3.1 is the block diagram of a passive two-port network used as a communication link. Controller design based on passive compensation requires one to obtain controller parameters which make the network be passive (i.e. satisfy the scattering theorem). The passive compensation method guarantees asymptotically stable operation in spite of any time delays, assuming the human operator, master, slave and environment can all be represented as passive systems. Anderson and Spong (1988), and later Niemeyer and Slotine (1990), showed that the stiffness between master and slave was effectively reduced by the passive communication law. This reduction of stiffness and the position drifting problem of velocity-force control (Van der ham, 1995) will be investigated in October and November of 1995.

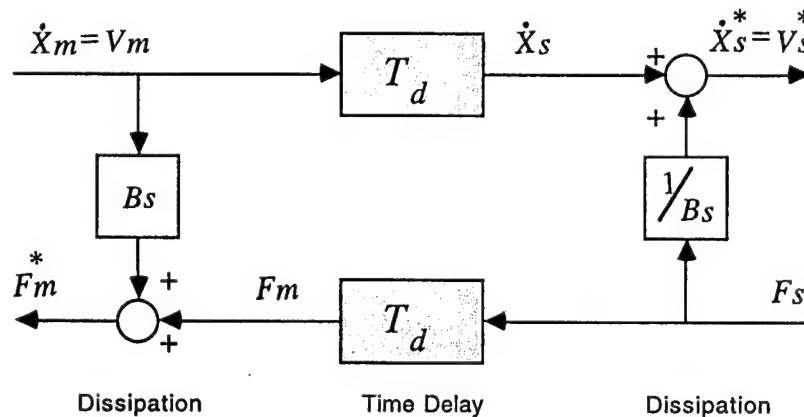


Fig. 3.1 Passive Compensation of a Communication Process in Teleoperation

A position-derivative (PD) controller will be designed for the motor control of the slave manipulator. To keep the dynamic and steady states identical in slave and master manipulator, the controller type of slave and master should be the same. Selecting the gains for master and slave controllers can be done partly by analysis and partly by experiment. For force fidelity, the position controller gains, e.g.  $K_s$  and  $B_s$  should be selected to make the system as stiff as possible. This comes at the expense of a larger

apparent inertia and increased damping in the system. Thus there is a trade-off when adjusting the gains for the passive communication law. Lawn (1992) gives gain and parameter settings appropriate for such experiments.

### **3.2.2. Demonstration of Various Control Approaches:**

Using different control techniques, namely Fuzzy Sliding Control, Predictor Display, Move-and-Wait, Supervisory Control, Passive Compensation etc., we will implement further human-in-the-loop teleoperation experiments on our established PHANToM master-slave system with different time delays and a real beam.

We will also perform laparoscopic telesurgery tasks and measure performance under different time delays. These experiments will be discussed in the next section.

### **3.3. EXPERT-NOVICE COOPERATIVE TELESURGERY**

At the current time we expect to run two complete sets of experiments: (i) telesurgery without time delays and (ii) telesurgery with time delays. These experiments will be done over short distances within the lab, but will be amenable for longer distance demonstrations through the use of the telecommunications link. It is hoped that it will be possible to move the master-side system to a local hospital for demonstration purposes.

The first set of experiments will permit us to develop guidelines for use in cases when delays are negligible, while the second will indicate what changes would be necessary given delays in communication.

#### **3.3.1 No delay experiments:**

September and October 1995 will be spent finalizing the form of the experiments--pretesting the tasks and developing the dexterity tests. Any problems with the equipment will be solved during this period. Tests with naive subjects will be conducted in November. As an "expert", either Dr. James Thompson, Mark Ottensmeyer or both will become familiar and well practiced at the various tasks during the pre-test period. It is assumed that a real surgeon working through a telesurgery system would have extensive experience with it, and be far along the learning curve with respect to its operation.

Subjects will first perform the dexterity tests and go through a pretest interview. These results will yield data that may permit us to determine if performance can be predicted based on objective measures other than direct tests with laparoscopic tasks. Then one of the laparoscopic instruments will be assigned to the surgeon, the assistant being given the other two, and the series of tests will be performed. A series will include a set of each of the different elemental tasks with order counterbalanced to prevent learning bias. If practical

we will assign the tools and have the subject perform each task again to allow inter-subject comparison.

In the no-delay case the surgeon and assistant will be separated by a distance of only a few feet and by a curtain so that the surgeon will not have direct vision of the "remote" site. The same video image will be presented to each, and direct audio communication will be available to the pair. This arrangement provides all the separation of surgeon and assistant necessary to evaluate tele-cooperation, despite the short distance.

The tests will be recorded by two video tapes: one from the CCD laparoscope and one from an external camcorder. Timing and errors will be determined from the tapes, and analysis of these data will occur in November and December and will contribute to the any modifications necessary for the time delay experiments in early 1996.

### **3.3.2 Time delay/remote venue experiments:**

In the first few months of 1996 we will prepare and conduct experiments to evaluate the effects of time delay on the surgeon-assistant interaction. Given these results, different recommendations may be made on how best to coordinate tasks for different levels of delay.

The experiments themselves will be very similar to those used in the no-delay case. Assistants will go through the dexterity tests and interview, and tools and tasks will be assigned in the same way. Keeping experimental format the same except for the delay aspect will permit us more easily to compare the two cases.

Based on the findings of the simplified environment time delay experiments, one or two of the time delay solution schemes will be used in the laparoscopy task experiments.

### **3.3.3 Paramedic Skill Evaluation/Modelling in Cooperative Telesurgery:**

There are four major variables here: the surgeon, the assistant, the diagnostic/therapeutic task, and the time delay. In practice, the assistant would likely be a paramedic who will have some experience with trauma patients, but will not have the diagnostic ability, knowledge base, surgical skill and medical decision making ability of the surgeon. Different paramedics will have different strengths and weakness.

It has been suggested that if these strengths and weakness can be quantified (e.g. by visuo-spatial, manual dexterity, personality, and other tests), then combined with the circumstances of a given procedure, a surgeon will be able to look up in a database the best way to allocate tasks between him or herself and the paramedic. To develop such a database would require a model of the interaction which would use test results and circumstance as inputs and a near optimal task assignment scheme as an output. Using the

results of our experiments it may be possible to begin to develop such a model, given the test results of the subjects, and their subsequent performance in the surgical training tasks.

### **3.3.4 Data analysis and reporting:**

Analysis of the fall '95 experiments will begin in November '95 and continue until complete (expected January '96 at the latest). The winter '96 tests will likely be evaluated beginning in March or April '96. Based on this information, conclusions and guidelines will be drawn up covering the interaction given various time delays and subject competency. Final reports will be complete in the summer of 1996, and any papers will be under way by then.

Simple demonstrations of the equipment are ready now, and will become more extensive as the experiments go ahead. One of the final demonstrations will include an animal tissue dissection test, likely under various combinations of surgeon-assistant cooperation.

## **4. CONCLUSIONS**

After the first year's effort, significant steps have been made in pursuit of a solution to the time delay problem and in developing guidelines for the interaction between tele-surgeon and local assistant. A human-in-the-loop tele-surgery simulation system has been developed, including a force reflecting master-slave system, a novel remotely controlled surgical tool and test apparatus to provide objective measures of performance. Various control schemes to provide stable force feedback during teleoperation have been studied, including Fuzzy Sliding Control, and will be implemented in the coming months for use in experiments based on surgical training tasks. The next year's work will include experiments with novice assistants to determine how best to allocate tasks between tele-surgeon and assistant, in both no-delay cases, and cases with delay, using the best of the control schemes. To demonstrate proof of concept, a tele-communications method will be used to permit the locales of the surgeon and the task to be separated by non-trivial distances.

## REFERENCES

- Anderson, R.J., Spong, M.W., Bilateral Control of Teleoperators with Time Delay. Proc. IEEE Intl. Conf. SMC, Vol.1, pp131, Beijing, China, Aug., 1988.
- Brooks, T.L., SUPERMAN: A System for Supervisory Manipulation and the Study of Human-Computer Interactions, SM thesis, Cambridge, MA:MIT, 1979.
- Buzan, F., Control of Telemanipulators with Time Delay, ScD Thesis, Cambridge, MA: MIT, 1989.
- Buzan, F., and Sheridan, T.B., A Model-based Predictive Operator Aid for Telemanipulators with Time Delay, Proc. of 1989 IEEE Intl. Conf. on SMC, pp14-17, Cambridge, MA, Nov., 1989.
- Bejczy, A.K., Bekey, G.A., Revetta, A., Taylor, R.H., A Research Methodology for Telesurgery with Time Delay, First Intl. Symposium on Medical Robotics and Computer Assisted Surgeries (MRCAS), Pittsburg, 1994.
- Conway, L., L.R. Volz and M. Wilker, Teleautonomous Systems: Methods and Architectures for Intermingling Autonomous and Telerobotic Technology, Proc. of 1987 IEEE Intl. Conf. on Robotics and Automation, March 31-April 3, Raleigh, NC: 1121-1130, 1987.
- Faraz, A., Payandeh, S., Nagy, A.G., Issues and Design Concepts in Endoscopic Extenders, 6th IFAC/IFIP/IFORS/IEA Symposium, MIT, June, pp 109-114, 1995.
- Ferrell, W.R., Remote Manipulation with Transmission Delay, IEEE Trans. Human Factors in Electronics, HFE-6, No.1, 1965.
- Ferrell, W.R., Delayed Force Feedback, Human Factors, pp 449-455, October, 1966.
- Ferrell, W.R., and Sheridan, T.B., Supervisory Control of Remote Manipulation, IEEE Spectrum 4, No.10, pp 81-88, October, 1967.
- Funda, J., Lindsay, T.S., Paul, R.P., Teleprogramming: Toward Delay-Invariant Remote manipulation, Presence, Vol.1, No.1, MIT Press, 1992.
- Hirzinger, G., Brunner, B., Dietrich, J., and Heindle, J., Sensor-Based Space Robotics -ROTEX and Its Telerobotic Features, IEEE Trans. on RA, Vol.9, No.5, 1993.



Kavoussi, L.M., Bender, J.S., Moore, R.G., Zenilman, M.E., Partin, A.W., Satava, R.M., Telerobotic Assisted Laparoscopic Surgery: Initial Laboratory and Clinical Experience, *Urology*, Vol. 44, No. 1, pp 15-19, 1994

Law, C.A., Hanaford, B., Performance Testing of Passive Communication and Control in Teleoperation with Time Delay, *Proc. IEEE Conf. on Robotics and Automation*, pp776-783, 1993.

Lee, Chuen Chien, Fuzzy Logic in Control Systems: Fuzzy Logic Controller - Part I, *IEEE Trans. on SMC*, Vol.20, No.2, 1990.

Niemeyer, G., Slotine, J.J., Stable Adaptive Teleoperation, *IEEE Journal of Oceanic Engineering*, Vol.16, pp152-162, Jan, 1991.

Ottensmeyer, M., Cooperative Telesurgery, *Proc. 1995 CIDMS Winter Conference*, MIT, pp 1-9, Jan. 1995.

Partin, A.W., Adams, J.B., Moore, R.G., Kavoussi, L.R., Complete Robotic Assisted Laparoscopic Urologic Surgery: A Preliminary Report, The James Buchanan Brady Urological Institute, The Johns Hopkins Medical Institute, Baltimore, U.S.A, March 13, 1995.

Pedrycz, W., Fuzzy Control and Fuzzy Systems, second edition, John Willey & Sons Inc., 1993.

Rininsland, H.H., Basics of Robotics and Manipulators in Endoscopic Surgery, *Endoscopic Surgery and Allied Technologies*, Vol.3, pp154-159, 1993.

Sheridan, T.B., Telerobotics, *Automatica*, Vol.25, No.4, pp 487-507, 1989.

Sheridan, T.B., Telerobotics, Automation, and Human Supervisory Control, MIT Press, 1992.

Sheridan, T.B., Space Teleoperation Through Time Delay, Review and Prognosis, *IEEE Trans. on Robotics and Automation*, Vol.9, No.5, pp. 592-606, Oct., 1993.

Slotine, J.J., Li, W., *Applied Nonlinear Control*, 1991.

Steele, R.J., Hosking, S.W., Chung, S.C., Graded Exercises for Basic Training in Laparoscopic Surgery, Journal of the Royal College of Surgery, Edinburgh, Vol. 39, No. 2, pp112-116, 1994.

Van der ham, A.A., Hondered, G., Jongkind, W., A Design for a Man Machine Interface for the Teleman Dexterous Gripper, 6th IFAC/IFIP/IFORS/IEA Symposium, MIT, June, 1995.

## APPENDIX A: FUZZY LOGIC CONTROL

Fuzzy logic is much closer in spirit to human thinking and natural language than traditional logic. Essentially it provides an effective means of capturing the approximate, inexact nature of the real world. A fuzzy logic controller (FLC) is a set of linguistic control rules which, in combination, result in an algorithm to map quantitative inputs to quantitative outputs. The methodology of the FLC is very useful when the processes are too complex for analysis by conventional quantitative techniques or when the available source of information can only be interpreted qualitatively, inexactly, or uncertainly. Thus fuzzy logic control may be viewed as a step toward a rapprochement between conventional precise mathematical control and human-like decision making.

Here is an example of FLC with approximate inference (Mamdani's Approach). If there exist  $N$  rules in the fuzzy control system, the  $i$ th rule is in the form of

IF inputs  $x_1 = A_i$ ,  $x_2 = B_i$ , THEN  $u = C_i$ .

Let  $x_{10}$ ,  $x_{20}$  be the inputs of  $x_1$ ,  $x_2$  correspondingly, so the truth value of the premise (or membership) can be expressed as

$$\mu_i = \mu_{A_i}(x_{10}) \wedge \mu_{B_i}(x_{20})$$

where  $\mu_{A_i}(x_{10})$  is the membership of  $x_{10}$  pertaining to fuzzy set  $A_i$  and  $\mu_{B_i}(x_{20})$ , membership of  $x_{20}$  pertaining to  $B_i$ , and " $\wedge$ " is an operator, which can be defined as "minimum". Then, the membership of the control output is

$$\mu_c(z) = \bigvee_{i=1}^N \mu_{C_i}(z)$$

where " $\vee$ " is an operator, which can be defined as "maximum". Therefore the output (fuzzyfication, or fuzzy decision making) can be obtained from the centroid formula.

$$u = \frac{\sum \int \mu_{C_i}(z) z dz}{\sum \int \mu_{C_i}(z) dz}$$

The inference process can be described in the following figure.

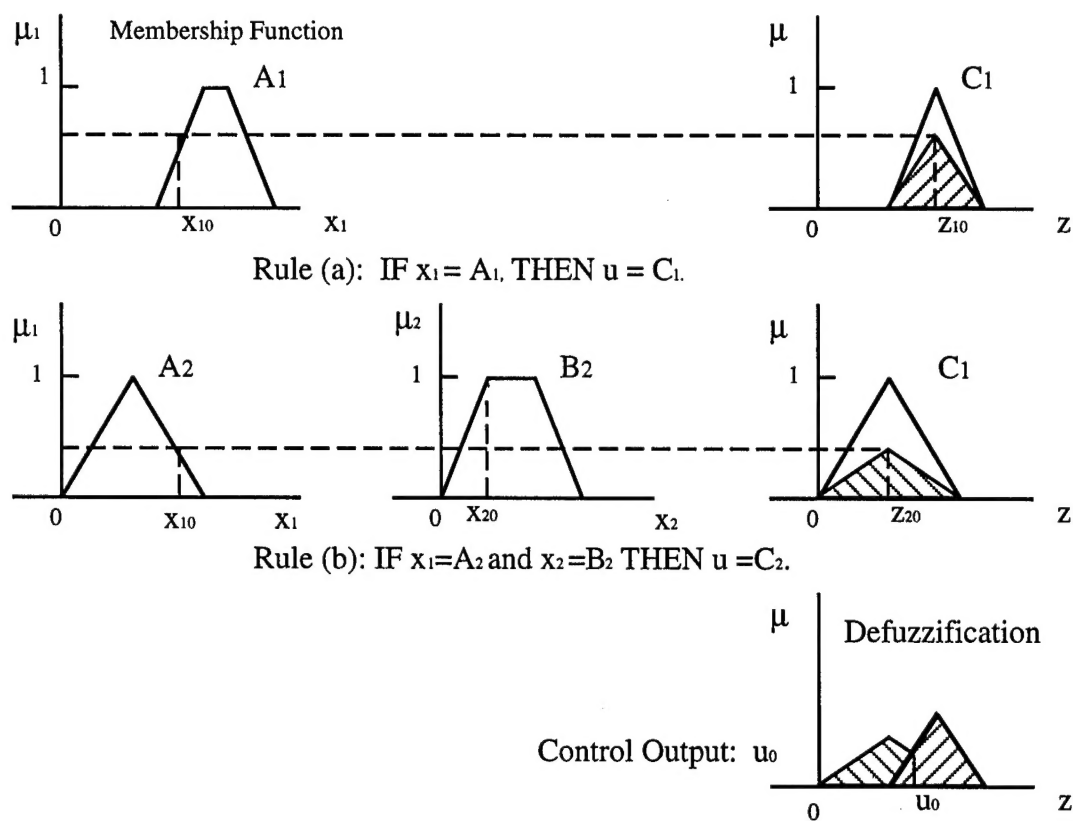


Fig. AP-1 Inference Process of Fuzzy Control